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New sustainable fruit packaging

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Abstract
In order to ensure food safety, quality, and supply chain efficiency, the global fruit industry must immediately address the environmental effects of traditional plastic packaging. Sustainable fruit packaging options are more important than ever due to the rising demand for fruits worldwide and growing environmental concerns. Traditional plastic packaging greatly increases pollution and degrades the environment, even though it is good at keeping food fresh and cutting down on waste. This chapter reviews creative methods for packaging fruit sustainably that emphasize reusable containers, biodegradable materials, and smart packaging technologies. Furthermore, the integration of digital manufacturing through 3D printing and the application of nanomaterials are highlighted as transformative approaches to enhancing the structural integrity and antimicrobial properties of eco-friendly packaging. The study further emphasizes the transition towards a circular economy by advocating for the reuse and infinite recyclability of materials, ensuring a closed-loop system that minimizes waste and resource depletion. The study further emphasizes the transition towards a circular economy by advocating for the reuse and infinite recyclability of materials, ensuring a closed-loop system that minimizes waste and resource depletion. By addressing these issues, sustainable fruit packaging can contribute significantly to a circular economy, reducing waste and promoting environmental stewardship in the agricultural supply chain.

Keywords: Active packaging, 3D printing, fruit packaging, fruit shelf life, intelligent packaging, sustainable packaging

Introduction
Fruit demand has increased globally as a result of population growth and health-conscious consumers looking for nutrient-dense food options (Siegel *et al*., 2014) [1]. However, worries about the effects of conventional packaging techniques, especially those that use plastics, on the environment have increased as a result of this increase in consumption (Van der Berg, 2016). Plastic packaging undoubtedly contributes significantly to food safety, but problems with its non-biodegradable nature, recycling, and the poisonous chemicals it releases into food and soil present serious risks to human health and the economy (Khandeparkar *et al*., 2024) [2]. The development of new packaging materials with an emphasis on food safety, quality, and the environment is also required by global packaging regulations and awareness of plastic packaging (Guillard *et al*., 2018) [3]. Therefore, there needs to be immediate focus on using bio-sourced polymers as alternatives to non-biodegradable food packaging materials (Dutta and Sit, 2024) [4]. As a result, moving toward sustainable fruit packaging is not just a choice; it is a necessity to meet global environmental sustainability targets and lessen the agri-food industry's ecological footprint (Moreschi, 2022) [5]. The novel developments in environmentally friendly fruit packaging are examined, along with their applications and obstacles to wider adoption. By focusing on biodegradable materials, active and intelligent packaging systems, and circular economy principles, this provides a comprehensive understanding of the transformative potential of sustainable packaging solutions (Ahmed *et al*., 2022) [6].

Conventional Fruit Packaging
The mainstays of conventional fruit packaging are polystyrene trays, clamshell containers, and plastic films because of their strength, portability, and capacity to maintain freshness throughout storage and transit (Bhardwaj *et al*., 2021) [7]. These materials are preferred due to their affordability, portability, and outstanding ability to shield fruits from microbial contamination, moisture loss, and mechanical harm. Transparent plastic films are a popular option for retail displays because they improve product visibility while preserving freshness. Because of their easy handling and cushioning qualities, polystyrene trays are frequently used in conjunction with shrink wraps. Apart from offering physical safeguarding, conventional packaging is essential for prolonging the shelf life of fruits by establishing regulated conditions that lower respiration rates and postpone ripening (Shankar and Jaiswal, 2023) [8]. Through the use of plastic films with selective permeability, modified atmosphere packaging (MAP), for instance, controls gas exchange and successfully preserves fruit quality throughout storage and transportation (Rennie and Sunjka, 2017) [9]. Similar to this, vacuum-sealed packaging reduces oxygen content, which delays spoiling and microbial activity (Degirmencioglu *et al*., 2011) [10].
Notwithstanding these benefits, it is impossible to ignore how conventional fruit packaging affects the environment. Since the majority of these materials are not biodegradable and come from non-renewable fossil fuels, plastic waste ends up in landfills and the ocean (Ncube *et al*., 2020) [11]. Although plastic is good for protecting products, its durability allows it to linger in the environment for hundreds of years, which damages wildlife and contributes to

pollution. Furthermore, these materials' manufacture and disposal contribute to climate change by releasing greenhouse gases (Wilcox *et al*., 2016) [12].

The intricacy of sorting various plastic types and contamination from organic residues pose serious obstacles to efforts to recycle traditional packaging materials. Consequently, a significant amount of these materials wind up as waste, and recycling rates for them continue to be low. The necessity to switch to more ecologically friendly and sustainable alternatives that strike a balance between cost, ecological impact, and functionality is underscored by these limitations (Alaghemandi, 2024) [13].

Issues on Plastic Packaging

The US economy loses about 17–21 billion dollars annually due to plastic pollution, which is the second largest source of greenhouse gas emissions after incineration, despite its many benefits. Both developed and developing nations contribute to the accumulation of plastic waste, and ocean plastic pollution is a global issue (Basuhi *et al*., 2021) [14]. Each year, million tons of plastic debris enter the ocean, with the majority coming from developing nations with low incomes (Jambeck *et al*.,2018) [15].

1. **Environmental Pollution:** The enormous amount of waste that ends up in landfills and the oceans due to plastic packaging disturbs ecosystems and puts marine life in jeopardy (Norton, 2020) [16].
2. **Non-biodegradability:** Conventional plastics damage the environment over time because they take centuries to break down.
3. **Toxicity:** When plastics decompose, dangerous chemicals are released into the soil and water, endangering the health of people and the environment.
4. **Resource Depletion:** Petroleum and other non-renewable resources are used extensively in the manufacture of plastics, which leads to resource scarcity and environmental deterioration (Rhein and Schmid, 2020) [17].

Strategies for Bio-Sourced Alternatives

1. **Biodegradable Plastics:** These plastics, which are made from renewable resources like cornstarch, sugarcane, or cassava that function similarly to conventional plastics but decompose more quickly in natural settings**.**
2. **Compostable Materials**: Polylactic acid (PLA) and polyhydroxyalkanoates (PHA) are compostable under industrial conditions, offering a sustainable solution for fruit packaging (Razman *et al*., 2022) [18].
3. **Natural Plant Fibers:** Making strong and biodegradable packaging solutions out of materials like bamboo, hemp, and palm leaves.
4. **Mycelium packaging:** A novel material made from fungal mycelium that can be composted and used in place of polystyrene in fruit trays and containers.
5. **Edible Packaging:** Fruits can be protected by edible coatings and wraps made of seaweed, proteins, or polysaccharides, which eliminates the need for external packaging (Janowicz *et al*., 2023) [19].
6. **Recycled Paper-Based Solutions:** A low-cost and environmentally friendly substitute for plastic is made possible by molding recycled cardboard and paper pulp into trays and containers (Jarwar *et al*., 2024).

Types of Materials for Sustainable Fruit Packaging

1. Biodegradable and Compostable Polymers

Polymers that are both biodegradable and compostable have become popular substitutes for traditional plastic. Due to their environmentally friendly qualities, materials like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based composites are becoming more and more popular. These polymers have less of an impact on the environment over time because they break down naturally into non-toxic components (Abdul Khalil *et al*., 2018) [20].

1.1 Polylactic Acid (PLA):A popular option for environmentally friendly fruit packaging is polylactic acid (PLA), which is made from renewable resources like sugarcane and corn starch (Patil *et al*., 2021) [21].Because of its superior mechanical qualities, transparency, and food safety, PLA is especially well-suited for uses like produce trays and clamshell containers. Its ability to decompose under industrial settings, which guarantees that it disintegrates into non-toxic components without leaving hazardous residues, is one of its main advantages. In contrast to conventional plastics, PLA has significant drawbacks, such as brittleness, heat sensitivity, and expensive production. Research is still being done to improve its qualities; for example, combining PLA with other materials can lower costs while increasing flexibility and thermal stability (Kumari *et al*., 2022) [22].

1.2 Polyhydroxyalkanoates (PHA):PHA is made by microbial fermentation and is very adaptable and biodegradable (Koller, 2018) [23]. Because PHA can preserve structural integrity while being environmentally friendly, it is a great material for fruit packaging. It is appropriate for safeguarding fruits during storage and transportation due to its high resistance to water and UV rays. Furthermore, PHA's biodegradability guarantees that the packaging breaks down organically without leaving harmful residues, which is consistent with the ideas of the circular economy (Park *et al*., 2024) [24]. Another aspect of PHA's adaptability is its capacity to be tailored to meet different packaging requirements. For example, it is perfect for modified atmosphere packaging (MAP) applications because it can be designed to have particular barrier qualities that control gas exchange (Meereboer *et al*., 2020) [25]. By reducing respiration and postponing spoiling, these characteristics aid in preserving the freshness and quality of fruits. Furthermore, PHA mixes well with other biopolymers to improve its mechanical qualities, offering a strength-to-flexibility balance that is essential for handling and transportation (Ilyas *et al*., 2020) [26].

In addition to its practical uses, PHA production promotes sustainability by using renewable feedstocks like waste streams or agricultural byproducts. This promotes waste valorization in addition to lowering dependency on virgin resources. Additionally, a closed-loop system that reduces environmental impact can be created by integrating the production process with wastewater treatment systems. To make PHA more widely available, improvements in microbial strains, fermentation techniques, and scaling

technologies are necessary, as the comparatively high cost of production continues to be a barrier (Bhola *et al*., 2021) [27].

1.3 Starch-Based Composites: Natural, renewable resources like corn, potato, or cassava starch are used to make starch-based composites. Their cost-effectiveness and biodegradability are well known, which makes them a desirable option for environmentally friendly fruit packaging (Pei *et al*., 2024) [28]. These substances can be used alone or combined with other biopolymers to improve their characteristics. Because they offer a more environmentally friendly option to conventional plastics, starch-based composites are essential to sustainable fruit packaging. Their excellent barrier qualities against carbon dioxide and oxygen make them especially useful in applications like fruit coatings, trays, and films (Gamage *et al*., 2022) [29]. These characteristics aid in preserving the fruits' quality and freshness throughout transportation and storage. Additionally, starch-based materials' natural origin lessens reliance on fossil fuels, which is consistent with sustainability ojectives. The hydrophilic character of starch-based composites, however, presents problems with mechanical durability and water resistance. In order to get around these restrictions, starch is frequently combined with hydrophobic substances chemically or physically (Ojogbo *et al*., 2020) [30]. These improvements guarantee improved performance in real-world applications by strengthening and enhancing the material's flexibility and water resistance. The compatibility of starch-based composites with current manufacturing procedures is another important benefit, as it facilitates a more seamless shift from conventional to environmentally friendly packaging systems (Hossain *et al*., 2024) [31]. Additionally, they can be designed to include active packaging components, like antimicrobial agents, which increase fruit shelf life and cut down on waste. These composites hold promise for the fruit packaging sector as research focuses on optimizing them to balance sustainability, cost, and functionality (Jayarathna *et al*., 2022) [32].

2. Natural Fiber-Based Materials

Natural fiber-based packaging, like that made from wheat straw, sugarcane bagasse, and banana fibers, has shown a lot of promise. These products encourage waste valorization and lessen resource depletion by utilizing agricultural waste (Akter *et al*., 2022) [33].There has been considerable interest in natural fiber-based packaging materials for fruit packaging due to the growing demand for sustainable and eco-friendly alternatives. In addition to reducing the environmental impact of plastic packaging, these materials provide the functionality necessary for fruit preservation and protection (Srivastava *et al*., 2022) [18]. The plant-derived fibers that are used to construct natural fiber products include jute, coir, hemp, flax, sisal, and bamboo. As well as being biodegradable and lightweight, these fibers also exhibit excellent mechanical properties like tensile strength and flexibility (Thapliyal *et al*., 2023) [35]. Mats, trays, nets, and molded pulp products can all be made from these materials, depending on their application. To make them more moisture resistant, durable, and barrier-friendly, they can also be infused with bio-based polymers or coatings (Crini *et al*., 2020) [36].

3. Reusable and Recyclable Solutions

In the fruit packaging sector, progress toward recyclable and reusable materials has been spurred by the increased demand for environmentally friendly packaging options. Producers may drastically cut waste, lessen their impact on the environment, and encourage sustainable practices by using materials that can either be recycled back into the manufacturing cycle or reused several times (Hussain *et al*., 2024) [37].

3.1 Corrugated Cardboard: Because of its durability, adaptability, and recyclable nature, corrugated cardboard has long been a preferred material for fruit packing. The requirement for virgin raw materials is decreased because it is easily recycled into new paper goods and is made from sustainable resources like wood pulp.Fruits are shielded from harm during storage and transit by the superior cushioning and stress absorption offered by the fluted layers of corrugated cardboard (Oliver-Villanueva *et al*., 2025) [38].It is perfect for packing delicate fruits that need to be handled carefully, such as berries, apples, and peaches. Also it is simple to modify cardboard to make fruit boxes, trays, or cartons that meet particular measurements and storage requirements. Labeling and branding can be easily incorporated into the packaging through printed visuals, logos, or customer instructions. With recycling rates of over 80% in several nations, corrugated cardboard is a highly recyclable material. It can be recycled and used to make new cardboard or other paper goods. It is a great option for environmentally friendly packaging because it breaks down organically. Because cardboard is lightweight, shipping expenses can be decreased. In comparison to certain other packaging materials like glass or metal, it is also reasonably priced (Campean *et al*., 2017) [39].

3.2 Glass Containers: Glass is a classic material that can be recycled and reused, which makes it a great option for packaging high-quality fruit goods. Glass packaging is increasingly being used for fresh fruit in niche markets where sustainability and quality are valued, even if it is more frequently connected to processed or preserved fruits (such as jams, juices, dried fruits and syrups).Glass containers retain their quality and structural integrity even after repeated washings. They are therefore a durable choice for packing high-quality fruit items. Glass may be recycled endlessly without losing quality because it is 100% recyclable (Geueke *et al*., 2018). This closed-loop recycling method saves resources and drastically cuts waste. Because glass is chemically inert and non-porous, it has no effect on the fruit it contains. This guarantees that the product will stay fresh, uncontaminated, and retain its original flavor and scent. It offers a superior defense against light, moisture, and oxygen, extending the shelf life of fruits and fruit-based goods. Glass containers are linked to

high-end and luxurious goods. The perceived worth of premium fruits, like artisanal fruit gift sets or exotic berries, is increased when they are packaged in glass containers (Miranda *et al*., 2019) [41].

3.3 Metal Containers: For high-quality fruit goods, metal packaging—especially that made of aluminum and tin-plated steel is an additional recyclable and reusable option. Metal containers are becoming more popular for packaging fresh and dried fruits, while they are still more frequently used for canned fruits (Deshwal and Panjagari, 2020) [17].Metal containers have the same structural integrity as glass and can be reused again. Among the most recycled commodities worldwide are steel and aluminum, demonstrating how readily recyclable metal is. Recycling metal is an environmentally preferable alternative to creating it from raw resources because it requires a lot less energy. Metal containers are perfect for preserving fruits during storage and transit since they are incredibly strong and impervious to physical harm. They offer a superior defense against light, moisture, and oxygen, preserving the flavor and freshness of fruits. The visual appeal of high-end fruit items can be improved by designing metal packaging with eye-catching finishes, embossing, or printed branding (Miranda *et al*., 2019) [41].

A major step toward sustainability in the packaging sector is the use of recyclable and reusable materials, such as metal, glass, and corrugated cardboard, in fruit packaging. While glass and metal containers serve luxury markets by offering durability, aesthetic appeal, and reusability, corrugated cardboard provides an affordable and recyclable alternative for bulk and retail packaging. The fruit packaging sector may continue to strike a balance between sustainability, aesthetics, and practicality by utilizing advancements in material design and production techniques, opening the door to a more environmentally friendly future.

4. Edible coatings

Edible coatings are a cutting-edge, environmentally friendly technique that improves the fresh fruit's quality and shelf life. These coatings create an imperceptible, thin layer on the fruit's surface and are composed of natural, biodegradable polymers including starch, cellulose, and pectin. In addition to being suitable for human eating, this layer serves as a barrier to stop moisture loss, postpone ripening, and stop microbial contamination (Salehi, 2020) [42].

4.1 Starch: Made from corn, potatoes, or cassava, starch-based coatings are popular because of their capacity to form films, their biodegradability, and their affordability. These coatings provide the fruit's surface a smooth, protective layer and aid in preventing moisture loss (Basiak *et al*., 2019) [43].

4.2 Cellulose: Because it forms robust and flexible films, this plant-based polymer is frequently utilized in edible coatings. Water resistance and barrier qualities are improved by derivatives like methylcellulose and hydroxypropyl cellulose (Liyanapathiranage *et al*., 2023) [45].

4.3 Pectin: A natural gelling ingredient with superior film-forming qualities, pectin is extracted from fruit peels, including citrus and apple. It works especially well at decreasing oxygen permeability, which slows down the ripening and oxidation processes (Panahirad *et al*., 2021) [44].

4.4 Waxes and lipids: To increase water resistance, lipid-based ingredients like vegetable oils, beeswax, or carnauba wax are frequently added. These substances form a hydrophobic layer that keeps fruit from drying out while preserving its texture (Sangeetha *et al*., 2024).

4.5 Proteins: To improve the mechanical and barrier qualities of edible coatings, proteins such as casein (milk protein), whey, or soy protein are combined with other polymers. Additional functional agents, such antioxidants or antibacterial chemicals, may also be present in these coatings (Hauzoukim and Mohanty, 2020) [25].

4.6 Antioxidants: Components such as tocopherols (Vitamin E) and ascorbic acid (Vitamin C) are added to fruit to prevent oxidative damage, maintain color, and keep its nutritional value (Mieszczakowska-Frąc *et al*., 2021) [48].

4.7 Antimicrobial Agents: Included are natural antimicrobials such plant extracts or essential oils (like thyme, clove, or oregano oil)

Innovations in Packaging Technologies

1. Active packaging

In order to increase a product's quality, safety, and shelf life, active packaging refers to packaging methods that engage with the product either internally or externally. By mixing antibacterial agents and oxygen scavengers, it prolongs the shelf life of fruits. By adding useful components that aid in regulating variables like oxygen, moisture, and microbial activity, active packaging can greatly minimize spoiling, preserve freshness, and increase storage duration for fruits. In order to extend the shelf life of fresh produce, two crucial elements of active fruit packaging are oxygen scavengers and antibacterial agents (Rodriguez *et al*., 2024) [49].

Oxygen is the main element that hastens the decay of fruits. Flavor, color, and texture can all be lost as a result of oxidation brought on by oxygen exposure. Compounds like iron powder, ascorbic acid, or other metal-based agents are commonly included in oxygen scavengers. These substances react with oxygen to bind it and remove it from the package environment. This slows down the fruit's oxidation by lowering the oxygen content of the packing. By inhibiting the oxygen-catalyzed ripening and spoiling processes, the decrease in oxygen levels helps maintain the fruit's color, flavor, and texture. Because aerobic spoilage germs like molds and bacteria need oxygen to grow, oxygen scavengers assist prolong the shelf life of fruits by eliminating oxygen (Yu *et al*., 2024) [49].

In order to slow down ripening and spoiling, oxygen scavengers, which change the air composition inside the package (e.g., decreasing oxygen and boosting carbon dioxide or nitrogen), are frequently employed in MAP

(modified atmosphere packaging).Oxygen scavenger packaging can be particularly helpful for preserving the quality and avoiding browning of fresh-cut or pre-sliced fruits. Combining oxygen scavengers with ethylene absorbents can also assist regulate the ripening process, especially for ethylene-sensitive fruits like avocados, bananas, and apples (Badillo and Segura-Ponce, 2020) [51].

The purpose of antimicrobial compounds in active packaging is to prevent or reduce the growth of bacteria, molds, and yeasts that can contaminate and ruin fruits. These agents function by releasing antimicrobial compounds that either destroy or stop the growth of dangerous germs on the fruit's surface or within the packaging Antimicrobial agents, such silver nanoparticles, chitosan (a biopolymer made from chitin), or essential oils (like cinnamon or oregano oils), are placed in the packaging material and gradually move from the packaging to the fruit's surface to form a barrier that protects it. By rupturing microbial cell walls, interfering with their metabolic functions, or preventing bacterial and fungal reproduction, the antimicrobial drugs function. They thus aid in halting microbial activity-induced spoiling. Certain bacteria that are particularly problematic while handling and storing fresh produce, such *Salmonella*, *E. Coli*, or *Listeria*, can be effectively combatted by certain antimicrobial treatments (Esmaeili *et al*., 2022) [52].

2. Intelligent packaging

It is a cutting-edge form of packaging that uses technology to track and monitor a product's condition from manufacturing to consumption. Intelligent packaging for food items, such as fruits, uses sensors or indicators built into the packaging material to give real-time input on variables including temperature, humidity, gas levels, and freshness. This technology improves product safety, increases shelf life, and gives suppliers and customers useful information on the state of the product (Kuswandi, 2020) [53].

The product's temperature is tracked by the temperature sensors as it is being transported, stored, and displayed. Temperature sensors can notify customers or suppliers if the product has been exposed to circumstances that could cause spoiling (such as refrigeration failure), as temperature control is essential for maintaining the freshness of fruits. The humidity sensors determine the package's moisture content. Fruits must be kept at the right humidity levels to prevent mold growth and dehydration. Humidity sensors are able to detect any imbalance in moisture levels and provide feedback so that the user can take appropriate action, such as refrigeration or consumption (Alam *et al*., 2021) [7].Ethylene gas is produced by certain fruits, hastening the ripening process. The concentration of this gas can be detected by ethylene sensors in packaging, which can then indicate when the fruit is ripening too quickly or when the atmosphere inside the package needs to be changed. The pH or Volatile Organic Compound (VOC) sensors track pH variations or identify the presence of gases linked to spoiling, including sulfur compounds or ammonia, giving an early warning of possible microbial contamination or degradation (Nasir *et al*., 2024) [55].

Visual indicators known as Time-Temperature Indicators (TTIs) alter color based on the product's temperature history. For example, if the product has been stored outside of the ideal temperature range, a temperature-sensitive strip on the container may turn from green to red. TTIs aid in making sure that goods are stored properly, particularly perishables like fruits. Real-time feedback on the product's ripeness or freshness is given by freshness indicators (Liu *et al*., 2023) [56]. To indicate the degree of ripeness or the amount of time left before the product spoils, an indication for fruits like avocados or bananas could use color change or a digital display. Certain packing materials have indicators that change color according to the amount of nitrogen, carbon dioxide, or oxygen present. These Gas Composition indicators aid in determining the best time to eat the product and can be used to track the integrity of modified atmosphere packaging (MAP) (Giuggioli *et al*., 2016) [57].

3. 3D Printing

By layering materials, 3D printing, referred to as additive manufacturing, is a cutting-edge technique that makes it possible to create personalized packaging designs. 3D printing is being investigated more and more in the fruit packaging sector as a way to improve sustainability, cut waste, and save production costs. 3D printing is an intriguing and environmentally responsible substitute for conventional packaging techniques since it can be used to build complex, lightweight, and customized packaging solutions utilizing biodegradable materials. Digital models are used to direct the printing process in 3D printing (Zhou *et al*., 2021) [58]. Custom packaging designs can be precisely created by putting raw materials into a 3D printer, such as plant-based materials, biodegradable plastics, or biopolymers. 3D printing's main benefits for fruit packaging are its capacity to produce intricate geometries, use less material, and enable on-demand manufacturing (Dutta and Sit, 2024) [4].

Packaging designs can be customized via 3D printing to match the precise dimensions and form of individual fruits or fruit kinds. For instance, delicate fruits like peaches or strawberries might be packaged in specially designed containers to improve storage and transportation safety. It is simple to add unique package forms, textures, and logos into the design of the packaging. Businesses gain a competitive edge in the market because to this degree of personalization, which also improves the visual attractiveness of items and fortifies brand identification. Complex packaging structures, including honeycomb patterns or interlocking parts, can be made using 3D printing, which can increase the packing's strength and cushioning while using less material (Wang *et al*., 2023) [60].

Fruit packaging has a bright future to 3D printing's cost-effectiveness, sustainability, and customisation capabilities. 3D-printed fruit packaging has the potential to become a commonplace solution as technology and material choices develop, lowering waste, improving product protection, and giving customers access to higher-quality, more environmentally friendly packaging solutions. The use of biodegradable materials also paves the path for a more sustainable future in food packaging by satisfying the industry's increasing demand for environmentally friendly substitutes (Dutta and Sit, 2024) [4].

4. Minimalist Design

Minimalist design in sustainable packaging is an approach that prioritizes simplicity, functionality, and eco-friendliness. It aligns with sustainability goals by reducing

the use of materials, minimizing waste, and focusing on efficient and effective packaging solutions**.** The use of materials, such as paper, plastic, and other materials, is frequently decreased in minimalist design (Lin, 2024) [61]. Waste and the carbon footprint are lessened as a result of this. Packaging composed of recyclable, compostable, or biodegradable materials—like bamboo, recycled paper, or plant-based plastics is in line with sustainability and minimalism. Reducing dependency on virgin materials is the goal. The focus of a minimalist design is on visual elements' simplicity. As a result, there will be fewer patterns, colors, and typefaces, which will cut down on the usage of potentially hazardous inks and dyes. Labels and prints contain only the most essential details, reducing excess material usage for branding or messaging. Minimalist sustainable packaging avoids over-packaging. For example, eliminating secondary packaging layers, inserts, and excessive plastic wrap minimizes resource consumption. Packaging is designed to be lightweight and compact, which helps in reducing the need for excess packing materials (such as bubble wrap or foam peanuts).Containers that may be used again for storage are one example of minimalist packaging that can be made to be reused (Xiao *et al.*, 2024) [62].Clear recycling symbols or instructions are frequently easier to incorporate into simple packaging designs, which promotes appropriate disposal. Certain minimalist packaging options are made to be modular, which lowers materials and shipping costs by enabling several products to fit or stack together. In an effort to reduce waste and extend the life of products, minimalist packaging frequently aims for timeless appeal, which may persuade customers to keep and reuse packaging for longer (Garaszczuk, 2015) [63].

Case Studies

1. The Plastic Situation in East Africa

Rwanda was the first nation in the East African Community (EAC), which comprises of Burundi, Kenya, Rwanda, South Sudan, Tanzania, and Uganda, to outlaw plastic bags in 2008.

A ban on the "importation, manufacture, and use of plastic materials made of polymers of less than 30 microns" was tried to be announced by Uganda in 2007. However, in response to industrial criticism, the government suspended enforcement.

The Kenyan government banned "the use, manufacture, and importation of all plastic bags used for commercial and household packaging" in 2017 [39] via Gazette Notice No. 2356. This prohibition is a third effort to address the environmental annoyance in Kenya. Kenya took a less aggressive attempt to reduce the usage of plastic bags in 2007 by enacting a universal 120% levy on plastic bag use and prohibiting the production and importation of bags thinner than 0.03 millimeters. Kenya attempted to ban plastic bags up to 0.06 millimeters thick in 2011, four years later. Neither of these projects was carried out. Aaron Brooks remarked that the 2017 plastic bag ban was "one of the strictest bans on plastic bags in the world," with fines of up to $38,000 and jail terms of up to four years for a single offender. The Polythene Materials restrict Bill (EAC 2016), an act intended to govern and restrict the use, sale, manufacture, and importation of polythene materials, was released a year prior to this. Although carrier bags are the primary target of the prohibitions, generic plastic packaging—which is crucial packaging for FV (Fruit and Vegetable) products is also impacted by the regulation of polythene materials. This study concentrated only on FV products because, generally speaking, East Africans consume significantly less FV than the 400g per person that is advised daily. This is partially because these very perishable crops are only available during certain seasons. For this reason, locally processed FVs ought to close the seasonality gap. However, for this to occur, they require appropriate packaging that considers the views and needs of consumers and processors, which are the main emphasis of this study, as well as food safety, accessibility, and sustainability issues (Chen *et al*., 2021) [64].

2. A Case Study on Flat Peaches

Numerous bioactive characteristics of plant essential oils (EOs) emphasize their potent antibacterial and antioxidant capabilities. As a result, in recent years, there has been a particular focus on the use of EOs in active packaging. However, little research has been done on the inhibitory effect of EOs on plant product quality-degrading enzymatic systems during postharvest life. Following commercialization simulations (4 days at 22 °C), the effects of an EO active paper sheet on ethylene biosynthesis and quality (as well as associated quality-degrading enzymes) of flat peach (Prunus persica var. platycarpa) samples were examined during storage at 2 or 8 °C for 5 days (continental terrestrial transport) or 26 days (long maritime transport). Ethylene production was lowered by 40–50% and by as much as 70% following commercialization periods thanks to EOs emitted by active packaging. Lower levels of 1-aminocyclopropanecarboxylic acid (ACC) and ACC-oxidase activity were associated with these outcomes. Because EO active sheets prevent polygalacturonase and polyphenoloxidase, they also better conserved the physicochemical quality of the fruit, as measured by its soluble solids content, titratable acidity, color, and firmness. Additionally, upon storage at 8 °C and the subsequent commercialization period, EO-packaged samples showed increases in phenolic components (mostly catechin and cyanidin-3 glucoside) and total antioxidant capacity of up to 30 and 70%, respectively. In conclusion, EO active paper sheets preserved fruit quality, reduced ethylene production in flat peaches, and even enhanced bioactive substances that are beneficial to health (Benito, G. 2020) [65].

3. Case Study of Kiwi Fruit Supply Chain in Uttarakhand

With an emphasis on kiwi fruit in Uttarakhand, India, this case study investigates how sustainable packaging might improve the supply chain efficiency of perishable food commodities. The analysis shows how cutting-edge packaging options may increase sustainability, cut waste, and prolong shelf life while guaranteeing premium delivery from farm to table. The study emphasizes the significance of incorporating environmentally friendly techniques into the food supply chain by examining real-world applications (Trivedi *et al*., 2024) [66].

Advantages of Eco-Friendly Fruit Packaging

1. **Environmental Impact:** By conserving natural resources and minimizing waste, sustainable packaging helps create a cleaner, healthier world.
2. **Economic Efficiency:** Sustainable packaging frequently results in savings through lower waste

management costs and enhanced customer loyalty, despite potentially higher initial costs.

3. **Improved Brand Image:** Businesses that use eco-friendly procedures draw in eco-aware customers, which improve their standing in the market
4. **Improved Fruit Quality:** By preserving fruit freshness, advanced packaging technologies help to improve fruit quality for consumers (Hussain *et al*., 2024) [37].

Challenges in Implementing Sustainable Fruit Packaging

Although switching to sustainable fruit packaging has many advantages, there are a few issues that need to be resolved to guarantee its broad use:

1. **High Initial Costs:** The production costs of sustainable packaging materials, like natural fibers and biodegradable plastics, are frequently greater than those of conventional plastics. Small-scale producers may be deterred from implementing eco-friendly solutions by this price difference.

2. **Limited Raw Material Availability**: Certain raw materials, such cornstarch, bamboo, or hemp, are needed for the creation of bio-sourced goods, but they might not be easily accessible in every location. This reliance on supply chains for raw materials may lead to interruptions and increase expenses.

3. **Scalability Issues:** It is difficult to satisfy the needs of large-scale fruit farmers and retailers because many sustainable packaging options are currently made on a small scale.

4. **Consumer Awareness and Acceptance**: Educating consumers about the environmental benefits of sustainable packaging is essential. However, lack of awareness and resistance to change can hinder adoption, especially if eco-friendly alternatives are perceived as less durable or aesthetically appealing (Khandeparkar *et al*., 2024) [2].

5. **Regulatory Obstacles:** Manufacturers looking to expand their products internationally face compliance issues due to disparate nations' differing packaging material laws and standards.

6. **Performance Restrictions:** The quality and shelf life of packed fruits may be impacted by certain bio-sourced materials' lack of clarity, water resistance, or durability compared to traditional plastics.

7. **Infrastructure for Composting and Recycling:** A lot of sustainable materials call for specialized composting or recycling facilities, which might not be easily accessible. Inadequate infrastructure may result in inappropriate disposal and diminished environmental advantages.

8. **Economic and business Pressures:** Cost effectiveness frequently trumps sustainability in the fiercely competitive worldwide fruit packaging business. It's still difficult to persuade stakeholders to put long-term environmental advantages ahead of immediate financial profits (Moustafa *et al*., 2019) [69].

Government Regulations on Sustainable Fruit Packaging

By establishing guidelines, offering rewards, and ensuring adherence, government rules are essential in promoting the use of sustainable fruit packaging. Important regulatory actions consist of:

1. **Bans and Restrictions on Single-Use Plastics**: To lessen environmental pollution, many nations have banned or restricted single-use plastic packaging. For instance, the Single-Use Plastics Directive of the European Union promotes the use of sustainable substitutes while outlawing specific plastic products (Cipriani Schirrmacher, 2021) [70].

2. **Extended Producer Responsibility (EPR):** Manufacturers are held responsible for the full lifetime of their packaging, from production to disposal, under EPR regulations. Businesses must create environmentally friendly packaging and fund recycling initiatives

3. **Guidelines for Recycling and Composting:** Standards for compostability and recyclability are set by governments to guarantee that packaging materials can be treated efficiently. Certifications like EN 13432 and ASTM D6400 attest to the materials' compostability.

4. **Incentives and Subsidies:** Businesses who invest in environmentally friendly packaging materials and technologies can receive financial incentives like grants or tax reductions

5. **Mandatory Recycling Objectives:** Minimum recycling goals for packaging trash may be established by regulations. For example, member states are required to recycle a certain percentage of packaging materials under the EU Packaging and Packaging Waste Directive.

6. **Labeling specifications:** Governments mandate that packaging be clearly labeled to advise consumers about proper disposal techniques, like composting or recycling.

7. **Assistance with Research and Development:** Public funds are frequently given to research initiatives that seek to create novel and sustainable fruit packaging (Soundarrajan and Vivek, 2016).

Future Prospects of Sustainable Fruit Packaging

The combination of cutting-edge materials and technology with the ideas of the circular economy will determine the direction of sustainable fruit packaging in the future. The goal of research and development is to produce high-performance, reasonably priced solutions that meet a range of market demands. Governments, businesses, and academic institutions working together will be essential to the global adoption of sustainable practices (Moustafa *et al*., 2019) [69].

Conclusion

Reducing the environmental impact of the worldwide fruit industry requires the use of sustainable fruit packaging. The industry may drastically cut waste and carbon emissions by switching from conventional single-use plastics to environmentally friendly materials like recyclable, compostable, or biodegradable alternatives. Plant-based polymers, edible coatings, and fiber-based packaging are examples of innovative materials that show sustainability and usefulness can coexist without sacrificing fruit quality or shelf life. Sustainability initiatives are further strengthened by implementing circular economy concepts, such as recycling and reusing packaging materials.

However, a cooperative strategy is needed for the effective adoption of sustainable packaging. To encourage the creation of affordable solutions, set up legal frameworks, and raise public knowledge of the advantages sustainable practices have for the environment, governments, corporations, and consumers must collaborate. While protecting natural resources for future generations, scaling up sustainable packaging solutions can also open doors for green innovation and economic expansion. The environmentally friendly fruit packaging not only solves environmental issues but also satisfies customer demand for green products, opening the door to a more accountable and robust food supply chain.

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