JPPIPA 10(10) (2024)

Jurnal Penelitian Pendidikan IPA
Journal of Research in Science Education

http://jppipa.unram.ac.id/index.php/jppipa/index

Sustainability Development in the Context of Edible Coating for Fruits and Vegetables in Chemistry Learning: Qualitative Content Analysis

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Received: August 14, 2024
Revised: September 27, 2024
Accepted: October 25, 2024
Published: October 31, 2024

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DOI: 10.29303/jppipa.v10i10.8846

Abstract: This study aims to develop teaching-learning sequences (TLS) in the context of edible coatings for fruits and vegetables that integrate Education for Sustainable Development (ESD) in economic, environmental, and social aspects. TLS can be applied to create lesson plans or teaching materials in chemistry learning. This research used Qualitative Content Analysis, following four key stages: material collection, descriptive analysis, category selection, and material evaluation. Data were gathered from the analysis of fifty-eight literature sources and validated by five experts in terms of content validity. Validation experts are experienced four lecturers from chemistry education field and one doctoral student. The results of this research are as follows: TLS divided into four sections, postharvest losses, edible coating materials, preparation and characterization of edible coatings, and potential edible coatings to support sustainable living based on SDG-related points Zero Hunger (SDG 2), Good Health and Well-Being (SDG 3), Quality Education (SDG 4), Industry, Innovation, and Infrastructure (SDG 9), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), and Life on Land (SDG 15). The validation confirmed that the TLS content is appropriate for chemistry learning with ESD content.

Keywords: Chemistry Learning; Content Analysis; ESD; TLS; Edible Coating; Qualitative Content Analysis

Introduction

Agriculture is a fundamental pillar of human society. The Food and Agriculture Organization (FAO) estimates that by 2050, global food production will need to rise by 65-70% to accommodate the demands of an expanding population (FAO, 2009). However, Indonesia is grappling with a substantial food waste problem, with food waste making up 28.6% of the total waste. Agro-food systems worldwide contribute approximately one-third of all greenhouse gas emissions (Crippa et al., 2021). In Indonesia, the primary sources of Greenhouse Gas (GHG) emissions from the agro-food system are land-use change and forestry, which accounted for 48.7% of emissions in 2019, and agriculture, which contributed 9% (Wihardja et al., 2023). The problems are caused by the shortage of effective and cost-efficient postharvest preservation techniques, leading to significant and growing postharvest losses (PHLs) (Firdous et al., 2023). PHLs of fruits and vegetables encompass the degradation, spoilage, or decline in quality after harvest. These losses may arise from multiple factors, including mechanical injuries, physiological alterations, microbial contamination, and unfavorable environmental conditions (Riseh et al., 2023). Developing alternatives to preserve fresh-cut fruit is crucial for both consumers and merchants. For consumers, such alternatives ensure access to high-quality products that retain their properties without degradation. For merchants, these preservation methods provide economic benefits by extending the product's shelf life, allowing more time for sale (Iturralde-García

How to Cite:
Sulistyowati, D., Hernani, H., Supriatna, A., Fadhilah, A., & Aulia, A. (2024). Sustainability Development in the Context of Edible Coating for Fruits and Vegetables in Chemistry Learning: Qualitative Content Analysis. *Jurnal Penelitian Pendidikan IPA*, *10*(10), 8263–8275. https://doi.org/10.29303/jppipa.v10i10.8846

et al., 2022). Therefore, the implementation of innovative strategies is important.

Implementing postharvest technologies like preservation and storage practices is difficult in many developing countries due to the high initial costs required for constructing suitable facilities (Ray & Tomlins, 2010). Coatings and packaging materials are regarded as effective alternatives for extending the postharvest storage life of fruits and vegetables (Panahirad et al., 2021). However, the overuse of these treatments poses a negative impact on human health and the environment as it uses non-renewable raw materials (Kumar Rout & Singh, 2020). Consequently, it is crucial to develop environmentally sustainable and green alternative methods for the efficient preservation of fruits and vegetables (Riseh et al., 2023).

Edible coatings from biomaterials are increasingly in demand as one way to reduce PHLs. They are eco-friendly, biodegradable, and biocompatible, and prolong the shelf life of fresh fruits and vegetables by preserving their sensory attributes (Sapna et al., 2024). Edible coatings provide the potential to incorporate functional agents, such as antimicrobials and antioxidants, which safeguard food against pathogens and spoilage (Bhargava et al., 2020; Hernández et al., 2023). They enhance the nutritional quality of fruits and vegetables while maintaining their physiological attributes (Nain et al., 2021). Some research on edible coatings that have been done includes edible coating from randu leaf extract increased the shelf life of cucumber up to 9 days (Widyastuti et al., 2013). Through shrimp and crab chitosan, the shelf life of tomatoes was increased to 16 days (Wulandari & Ambarwati, 2022). Chitosan-CNC-$KMnO_4$ nanocomposite 5% resulted in banana fruit weight shrinkage of 4.87% and inhibited ripening with 16% sugar content in 5 days (Meysyaranta et al., 2022). Konjac flour and chitosan can increase the shelf life of red chilies up to 9 days (Rusdianto et al., 2024). Alginate-based and cinnamon essential oils can prevent strawberry spoilage up to day 5 (Siburian et al., 2021). Guava fruits coated with aloe vera gel and ethanol extract of guava leaves extended the shelf life to 15 days (Refilda et al., 2022).

Using natural materials like agricultural waste and plant extracts in edible coatings supports environmental protection by decreasing dependence on plastic packaging, thereby advancing sustainable agricultural goals (Flores-Contreras et al., 2024; Sonu et al., 2023). The International Panel on Climate Change (IPCC) reports that biopolymers significantly contribute to reducing the global temperature to 1.5°C by eliminating up to 20% of carbon dioxide levels, thereby providing environmental and sustainable benefits (Tabassum et al., 2023). Packaging materials derived from natural sources have the potential to transform the packaging industry, especially in terms of sustainability and eco-friendly food packaging. This area highlights the significant importance of the United Nations Sustainable Development Goals (SDGs), particularly zero hunger (SDG 2), industry, innovation, and infrastructure (SDG 9), and responsible consumption and production (SDG 12) (Das et al., 2023). Edible coating promotes healthier consumption, contributing to improved health and well-being (SDG 3). As a biodegradable and eco-friendly alternative to plastic packaging, our study also addresses the reduction of plastic waste (SDG 15) (Lakshan et al., 2024). The significance of specific sustainable technologies for enhancing food safety is highlighted in the United Nations Sustainable Development Goals, particularly concerning food safety and sustainable agriculture (SDG 2) and climate action (SDG 13) (Asrey et al., 2023).

To achieve the UN's Sustainable Development Goals, education systems must adapt teaching and learning methods to effectively convey and deepen understanding of sustainability as a complex concept (United Nations, 2022). Education for Sustainable Development (ESD) has been introduced as a vital response to sustainability challenges, with significant potential to enhance student outcomes by influencing their sustainability consciousness and shaping individual behavior to develop solutions in higher education (Ahel & Schirmer, 2023; Pauw et al., 2015). Learning innovation with ESD content to encourage awareness of sustainability (SDG 4). ESD-oriented courses that support systemic thinking to feel connected to nature and understand social, economic, and environmental values and increase attention to acting sustainably (Karaarslan & Teksöz, 2016). Integrating ESD into chemistry learning enhances cognitive learning outcomes, fosters a sustainable mindset, raises environmental awareness, and improves communication and collaboration skills (Ahel & Schirmer, 2023; Paristiowati et al., 2022; Pratiwi et al., 2023). The educational environment requires effective management to achieve educational goals (Murni, 2024).

ESD in the context of edible coatings for fruit and vegetables is designed through TLS. They are closely correlated, in that TLS can be designed to incorporate the principles and goals of ESD effectively. ESD emphasizes active learning methodologies that engage students in problem-solving and critical thinking. TLS can facilitate this by using driving questions and hands-on activities that encourage students to explore and address sustainability challenges (Rico et al., 2021). The TLS can serve as a foundation for developing lesson plans or teaching materials (Putri et al., 2024). The development of teaching materials requires a more thorough content analysis and enhanced content management to optimize learning outcomes (Kosim, 2024; Sanjaya et al., 2024).

Some TLS research in chemistry learning has been conducted on the topics of soap making from used cooking oil, eco-batteries, global warming, and the ores leaching processes using organic acids (Nurul Amalia et al., 2024; Octa Ningsi et al., 2024; Putri et al., 2024; Supriatna et al., 2024). TLS in the context of edible coating for fruit that integrates ESD aspects in each sub-context content has not been done so it becomes a novelty in this study.

Edible coatings are a sustainable technology to address the problem of postharvest damage in achieving the SDG goals of sustainable agriculture (SDG2) and climate change (SDG13). The use of agro-waste supports the goal of sustainable development in a circular economy (SDG1) (Asrey et al., 2023; Sridhar et al., 2023; Varghese et al., 2023). Therefore, this context has the potential to be used as learning content to increase students' sustainability awareness. The contextual content is organized in the TLS as the basis for preparing lesson designs or teaching materials for achieving several SDG goals.

Method

This study uses a qualitative content analysis method that refers to (Mayring, 2000). Qualitative content analysis is defined within this framework as an empirical and methodologically controlled approach to analyzing texts within their communication context. It follows specific content analytical rules and employs step-by-step models, without rash quantification. In this method, the analysis is divided into several stages based on (Mayring, 2000).

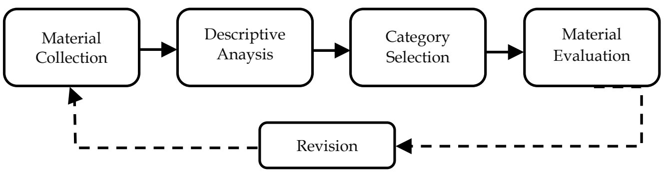

Figure 1. Stages of Qualitative Content Analysis

The first stage involves materials collection from reputable sources, including journal articles, conference papers, and review articles. These materials are documented which details the author, title, year, and code. The second stage involves descriptive analysis, where the gathered materials are thoroughly examined, with the results and content outlined in Table 1. The third stage is category selection, where the analyzed content is classified according to pedagogical and didactical aspects. The final stage is material evaluation, wherein the categorized concepts are assessed based on their correlations and interrelationships. A comprehensive review of these research activities from inception to conclusion is essential to formulate a systematic teaching-learning sequence (TLS).

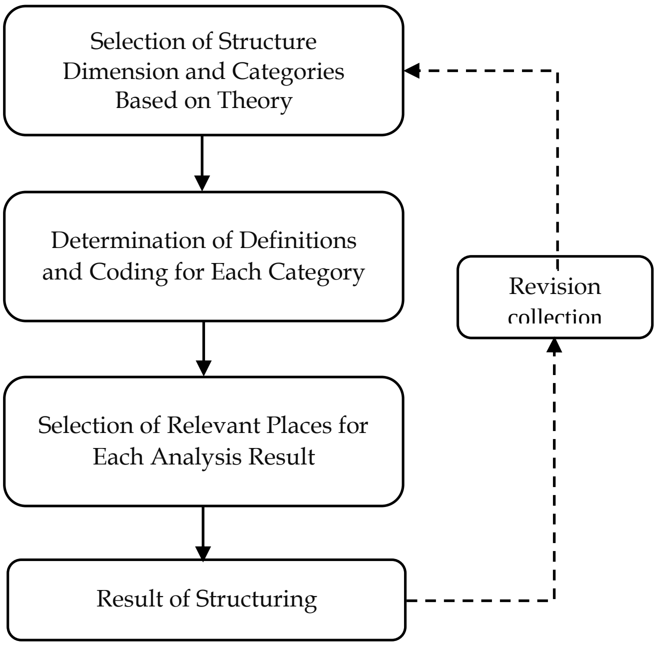

Figure 2. Stages of Qualitative Content Analysis Figure

Figure 2. illustrates the structuring process of qualitative content analysis employed in this research based on (Mayring, 2000). A data collection method is utilized, specifically the questionnaire technique, to gather expert validation data regarding the product. The expert validators consist of four lecturers specializing in chemistry education and one doctoral student in science education. To facilitate content validation, the research employs a questionnaire sheet for data collection. The gathered data is subsequently analyzed qualitatively, to process the questionnaire responses and summarize the information into descriptive insights.

Result and Discussion

Material Collection

Materials from reputable sources have been gathered from journal articles and books using search engines such as Springer and Elsevier. A total of forty-six pieces of literature were selected for further analysis. The sources were based on several keywords, including post-harvest damage, postharvest technology, biopolymers, lipids, plasticizers, antimicrobials, edible coating preparation, edible coating characterization, and sustainable agriculture.

Descriptive Analysis

In this stage, materials gathered from literature sources undergo descriptive analysis. The outcomes of this analysis are presented in Table 1.

Table 1. The Results of Analysis Descriptive

Content	Analysis Result
Postharvest Losses	Agricultural activities can be broadly categorized into three stages: pre-harvest, harvest, and post-harvest phases. Post-harvesting involves storage and processing. After harvest, farmers encounter numerous difficulties due to the escalating demand for agricultural production, and it is not easy to keep pace with the growing need for food processing, storage, and distribution (Kumar Kasera et al., 2024). PHLs of fruits and vegetables (VFs) presents a major challenge to the global agricultural sector (Sapna et al., 2024). The short shelf life of fruits and vegetables (VFs) accounts for approximately 70% of food waste, largely due to insufficient transportation and storage facilities. After harvest, VFs can lose around 20-30% of their value through processing, transportation, storage, and sales (Mohan et al., 2023). Physical factors to PHLs include inadequate temperature regulation, improper handling, insufficient packaging, transportation practices, road conditions, transit duration, and limited knowledge of produce quality causing mechanical injury in the fruits. Furthermore, fruit spoilage is primarily influenced by two key factors: physiological changes and microbiological activity (C. O. Perera & Smith, 2013). Physiological disorders include heat injury, cold injury, ethylene damage, carbon dioxide damage, and low oxygen (anaerobic) injury. The accessibility of food, both physical and social dimensions shows a significant correlation with food security (Wijayanti et al., 2024). For example, the effect of high temperatures on crops above 30°C results in high respiration rates. Respiration depends on a constant supply of oxygen, and any limitation in O_2 availability will cause an increase in CO_2 concentration, which can induce alcoholic fermentation and result in an undesirable odor. Accumulation of carbon dioxide, often due to inadequate ventilation during storage, transportation, and marketing, can lead to the eventual spoilage of the product. PHLs vegetables are primarily caused by the invasion of fungi, bacteria, insects, and other organisms, due to the decline in the plant's natural defenses after harvest. The susceptibility to these losses is influenced by genetics, mechanical injuries, stress conditions, and the stage of development, with older produce being more vulnerable (Singh et al., 2022). Climacteric fruits exhibit a marked increase in respiration and a surge in ethylene production as they ripen. Conversely, non-climacteric fruits maintain a constant respiration rate, with no significant rise in ethylene production during ripening. Injury to plant tissues enhances the rate of endogenous ethylene production and respiration. Harvest-related wounding can lead to a rapid escalation in respiration rate, accompanied by a concurrent increase in ethylene levels (C. O. Perera & Smith, 2013). Ethylene bursts in climacteric fruit with the onset of ripening and this autocatalytic ethylene ($H_2C{=}CH_2$) production leads to accelerated ripening and senescence of fruit. This gas significantly contributes to postharvest quality deterioration by altering skin color, cell turgor, and structural integrity, resulting in texture loss, increased respiration rates, and enhanced activity of cell wall-degrading enzymes. Consequently, the fruit becomes soft, mealy, and more susceptible to pathogen attacks, leading to elevated postharvest losses during handling, storage, and marketing (Asrey et al., 2023). For safeguarding the integrity of our food supply and extending its shelf life, the implementation of innovative strategies is important. Preservation and storage practices are postharvest technologies that are difficult to follow in many developing countries as they involve high initial costs for the construction of suitable facilities. Therefore, there is a need for postharvest technologies that are suitable for climatic fruit and vegetable commodities in developing countries (Ray & Tomlins, 2010). PHLs can be minimized through the application of edible coating. The use of edible coatings represents an innovative approach to postharvest preservation, valued for its ease of application, environmental friendliness, and effectiveness (Firdous et al., 2023). PHLs can be reduced through the use of edible coatings made from biomaterials. These coatings offer multiple advantages, including antimicrobial properties, regulated gas permeability, and moisture retention (Sapna et al., 2024). By managing the exchange of oxygen, carbon dioxide, aroma, and flavor compounds in food, edible coatings can improve food quality and extend the shelf life of fresh produce (Armghan Khalid et al., 2022). Various starch-based coatings, including carboxymethyl cellulose, guar gum, gum arabic, sago starch, and chitosan, have been shown to effectively reduce ethylene levels in fruits during storage (Bhan et al., 2022).
Edible Coating Materials	Edible coatings are categorized according to their polymeric matrix into the following types: polysaccharide-based (such as chitosan, starches, gums, cellulose, and alginate), lipid-based (including oils, fatty acids, resins, waxes, and glycerides), protein-based (such as zein, gluten, gelatin, whey, soy, and albumen), and composites, which are multilayered structures formed by combining hydrocolloids and lipids (Sapna et al., 2024). The use of biopolymers as a packaging material is witnessing a substantial increase globally owing to their considerable benefits over plastic, including biodegradability, availability, cost-effectiveness, non-toxicity, environmental friendliness, and biocompatibility (Perera et al., 2023). Additional components, including essential oils, antimicrobials, antioxidants, antibrowning agents, ethylene scavengers, moisture absorbers, nanoemulsions, nanoparticles, and bio-nanocomposites, can influence the physical and chemical properties of edible coatings (Basumatary et al., 2022). Plasticizers are the additives

Content	Analysis Result
	that play a crucial role in forming the film matrix. Coatings formulated with glycerol and sorbitol have been found to reduce mass loss and delay ripening. They are recommended for creating coatings from breadfruit starch to enhance post-harvest storage of tomatoes (Bezerra et al., 2019). Protein coatings improve mechanical properties, lipid coatings minimize water transfer, and polysaccharide coatings lower gas permeability (Pham et al., 2023). Edible coatings based on hydrocolloids (hydrophilic) such as polysaccharides and proteins gain commercial importance and affect extending shelf life, texture, color, and flavor (Asrey et al., 2023; Grzebieniarz et al., 2023). Some types of starch as edible coating materials include sorghum starch, avocado seeds, taro, porang, iles-iles, bananas, and potatoes (Cakrawati et al., 2017; Lakris Sembara et al., 2021; Ningsih et al., 2012; Radhiyatullah et al., 2015; Raharjo et al., 2012; Setiawan & Faizal, 2012; Susilowati & Lestari, 2019). Nevertheless, polysaccharides must be integrated with other materials due to their limited resistance to water migration (Nain et al., 2021). Chitosan is a widely used polysaccharide because it has antimicrobial and antioxidant properties. The effectiveness of chitosan coatings is influenced by factors such as concentration, degree of deacetylation, molecular weight, application method, and environmental conditions (Riseh et al., 2024). Chitosan can be obtained from shrimp shells and mangrove crab shells through HCl immersion extraction (Kinasih et al., 2019; Suptijah et al., 2011). The addition of chitosan can improve mechanical properties and antibacterial properties in edible coatings (Susilowati et al., 2021). Research by Yan et al showed that edible coatings made from chitosan and carboxymethyl cellulose extended the shelf life and preserved the quality of strawberries by reducing the levels of primary metabolites involved in amino acid, carbohydrate, and fatty acid metabolism, as well as the content of secondary metabolites involved in the metabolism of carotenoids, flavonoids, terpenoids, and phenylpropanoids (Yan et al., 2019). The effectiveness of proteins in forming edible coatings depends on the sequence of amino acids in the polypeptide chain and the interactions between these chains. These interactions largely dictate the coating's strength, as well as its permeability to gases and liquids (Chauhan, 2022). One of them is gelatin, which can be obtained from chicken feet through an acid process (Nurhakim et al., 2021). Lipid-based edible coatings possess pronounced hydrophobic properties, rendering them thick and fragile. Consequently, lipids are often combined with polysaccharides and proteins to enhance their mechanical properties (V. Gupta et al., 2022; Mironescu et al., 2021). One of them is beeswax, which can be obtained from a honeycomb by adding oleic acid and water into an emulsion (Mukdisari et al., 2016). Antimicrobials on VFs Antimicrobial substances damage the outer membrane of fungi and bacteria, resulting in the diffusion of functional compounds into the microbial cell membrane and inhibiting the replication of the microbial genome. This causes the microbial cells to die and the fruits and vegetables are free from microbial contamination (Sapna et al., 2024). Spirulina patensis is a microalgae with potential as an antibacterial that can suppress the growth of microorganisms by 7,100 colonies (Utomo et al., 2024). Antioxidants on VFs: Brown discoloration of fruit occurs due to phenol compounds catalyzed by the enzyme polyphenol oxidase (PPO). Edible coatings act as anti-browning agents, regulating the activity of the PPO enzyme by blocking oxygen from entering the fruit (Iturralde-García et al., 2022; Wang et al., 2023). Ascorbic acid, thiol-containing compounds (such as cysteine and glutathione), carboxylic acids (including citric and oxalic acids), phenolic acids, and resorcinols are frequently utilized as anti-browning agents. These compounds mitigate browning by converting o-quinones, generated through polyphenol oxidase (PPO) activity, back into their original phenolic substrate forms (Oduro, 2022; Panahirad et al., 2021). Essential oils The plants that contain essential oils are cinnamon, cloves, celery, eucalyptus, oregano, thyme, lemon and orange peel, ginger, and vanilla (Lamani & Ramaswamy, 2023; Pandey et al., 2022; T. Widyastuti et al., 2023). The addition of essential oils into edible coatings functions as an antifungal, antibacterial, and antioxidant agent (Kumar Rout & Singh, 2020; Pandey et al., 2023; Sarengaowa et al., 2023). Essential oils are utilized in edible coatings to enhance their properties and effectiveness, ultimately improving the physicochemical and sensory qualities and extending the shelf life of fruits and vegetables (Gupta et al., 2022).
Preparation and Characterization of Edible Coating	The formulation of edible coatings, particularly those derived from polysaccharide and protein biopolymers, entails a dissolution process accompanied by continuous stirring at a controlled temperature (Susilowati et al., 2021). In the case of composite edible coatings, an emulsifier is necessary to stabilize and integrate substances with differing affinities, such as hydrophobic lipids and hydrophilic compounds like starch, alginate, or pectin. The main parameters to determine the quality of edible coating application on fruit include gaseous and water vapor permeability, water solubility, sensory impact, mechanical strength, and firmness (Md Nor & Ding, 2020). The elevated water vapor permeability (WVP) is observed, as water vapor molecules are likely absorbed more quickly on the surface. The increase in hydrophilic groups in the biopolymer and interactions between the ingredients led to increased WVP value and surface hydrophilicity

Content	Analysis Result
	of the film (Hernández et al., 2023; Thakur et al., 2019). One of the physical properties of the film that needs to be considered is water solubility, which provides information about the durability of edible films in water (Loukri et al., 2024). Food products require materials with certain properties to ensure their quality during storage, distribution, and consumption (Filipini et al., 2020). Sensory evaluation was done on the color, taste, texture, and overall storage of the fruits at specified day intervals (Nasrin et al., 2020). Tensile strength (TS) and elongation at break (EAB) tests were performed to assess the mechanical properties of edible film. Mechanical properties are feasibility parameters that play an important role in the process of food packaging and storage (Qian et al., 2022). The EAB value is influenced by the intermolecular bond distance between the -NH_2 and -OH functional groups on polysaccharides such as starch and chitosan, the weakening of intermolecular bonds is due to the long distance between intermolecular bonds (Susilowati et al., 2021). Texture or firmness is a key quality parameter influencing consumer preference for fresh fruits (Nasrin et al., 2020). In addition, edible coatings can be characterized using instruments such as FTIR, SEM, and TG-DTG (Bezerra et al., 2019). Physiological changes, including weight loss, and nutritional changes, such as total sugar content and ascorbic acid levels, were analyzed at different maturity stages of tomatoes (Roy & Hossain, 2024). Daily testing was conducted to observe and estimate the time (in days) required for maturation/ripening, the development of off-flavors, spoilage, and the percentage of decay (Jhanani et al., 2024). The selection of coating methods is primarily determined by factors such as the type of fresh produce, hydrophobicity, coating material and thickness, viscosity, surface tension, density, emulsion stability, cost-effectiveness, and drying conditions (Mostafavi & Zaeim, 2020). Some methods are employed to fabricate edible coatings of VFs, such as dipping, spreading, spraying, and multilayer coating (Sapna et al., 2024). The development of coatings for less widely recognized fruits such as durian, rambutan, passion fruit, and mangosteen remains limited, particularly those utilizing lipid and protein-based formulations. To select the most suitable coating for tropical fruits, it is essential to have a thorough understanding of the specific characteristics of each fruit (Md Nor & Ding, 2020).
Potential Edible Coatings to Support Sustainable Living	The United Nations has outlined 17 goals, some of which are to promote environmentally friendly agriculture around the world. VFs play a critical role in the global agricultural economy, impacting not only economic and human health aspects but also environmental concerns, beyond their consumption as food (Oluwole et al., 2023; Springmann & Freund, 2022). An effective post-production system can enhance environmental sustainability by reducing excessive production, thus conserving limited land and water resources and by offering alternatives to the extensive use of chemical inputs, which may have harmful side effects. Advancements in post-harvest processes in rural areas can drive increased demand for agricultural raw materials. A comprehensive development of post-harvest practices has the potential to enhance income distribution in rural communities (Golob et al., 2002). Ensuring safe food production with optimal quality retention through environmentally sustainable methods is crucial. Relying on a single technology or approach is inadequate to address these challenges; however, managing ethylene with integrated sustainable technologies offers a promising and sustainable solution. These approaches align with the United Nations Sustainable Development Goals related to food safety and sustainable agriculture (SDG 2) and climate action (SDG 13) (Asrey et al., 2023). Using natural materials, such as agricultural waste and plant extracts, in edible coatings supports environmental protection by decreasing dependence on plastic packaging, thereby advancing sustainable agricultural goals (Flores-Contreras et al., 2024; Sonu et al., 2023). Edible coatings made from biopolymers are environmentally friendly, biodegradable, and biocompatible. They effectively extend the shelf life of fresh produce by preserving its sensory attributes (Sapna et al., 2024). The International Panel on Climate Change (IPCC) report indicates that biopolymers significantly contribute to reducing the global temperature to 1.50°C by eliminating up to 20% of carbon dioxide levels, thereby providing environmental and sustainable benefits (Tabassum et al., 2023).

Category Selection

The results from the content analysis conducted in the previous stage serve as a reference for developing categories within the sequence map. Categorizing aims to identify patterns of relationships and interactions among the components involved in the sequence map. The categorization results encompass four key areas. Firstly, it addresses postharvest losses, detailing the primary causes of fruit and vegetable damage, which include physical factors, physiological alterations, and microbial activity. Secondly, it explores edible coating materials, delineating the core and supplementary components employed in their creation. Biopolymers and lipids constitute the main ingredients, while plasticizers, emulsifiers, antimicrobials, and nanoparticles serve as additional elements. Thirdly, the preparation and characterization of edible coatings are discussed, outlining the coating process based on material selection and the characterization methods applied both pre- and post-fruit/vegetable application. Lastly, the potential of edible coatings in fostering sustainable living is examined, emphasizing their social, economic, and environmental benefits in alignment with Sustainable Development Goals

Material Evaluation

The concepts gathered from earlier stages are articulated into teaching-learning sequences (TLS).

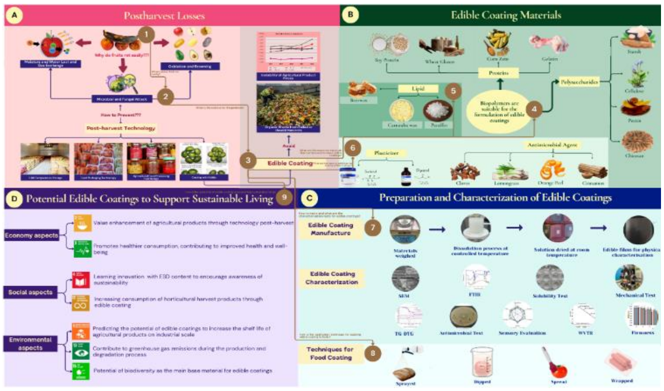

Figure 3. The TLS of Edible Coating for Fruit and Vegetables

The result of the TLS can be seen in Figure 3. On the TLS we categorized four sections into 1, 2, 3, and 4. Section 1 describes the causal factors and impacts of postharvest damage. Section 2 describes the main and additional ingredients that may be utilized in producing edible coatings. Section 3 describes preparing and characterizing edible coatings and application techniques on fruits and vegetables. Section 4 describes the potential of edible coatings to support sustainable living in economic, social, and environmental aspects. Each section consists of questions referring to another topic between each category marked by a number in small squares. Eight small boxes, interconnected by lines, represent the context of edible coating application on fruit, forming a cycle that illustrates the interrelatedness of each concept.

In section A connect squares A1 and A2, starting with a question: "What causes fruit rot easily?" to connect the topic of factors contributing to the rapid decomposition of locally grown fruit. The next question related to the sections to connect squares A2 and A3 with a question: "What is the solution to this problem?" as the question for students to research solutions of postharvest damage problems through various postharvest technologies. In section B, related to sections A and B with a question connected by squares A3 to B4: "What are the main raw materials that can be used to make edible coatings?" this question directs students to identify the physical and chemical properties of biopolymers such as polysaccharides and proteins as the main ingredients of edible coatings. Next, in section B, a question related to sections A and B connected by squares A3 and B5: "What are the main raw materials that can be used to make edible coatings?" this question directs students to identify the physical and chemical properties of lipid as the main ingredients of edible coatings. In the same section, a question related to sections A and B connected by squares A3 and B6: "What are the types of additives for making edible coatings?" students are tasked with identifying various additives, including plasticizers and antimicrobial agents derived from natural sources, that can enhance the physical or chemical properties of edible coatings. In C section, a question related to sections A and C connected by squares A3 and C7: "How to make and what are the characterization tests for edible coatings?" once the students have acquired knowledge of the components of edible coatings, they are instructed to design a method for producing and characterizing these coatings, both before and after their application on fruits and vegetables. Next, a question related to sections A and C connected by squares A3 and C8: "How is the application technique for applying edible coating to fruits?" this question is answered with various techniques to apply edible coatings on fruits. Finally, section A related to section D with a question to connect squares A3 and D9: "How is the potential of edible coating in supporting sustainable living?" the answer for this last question is a description of the potential application of edible coatings on fruit to increase its shelf life in supporting sustainable living in terms of the SDGs on economic, social and environmental aspects. Economic aspects include zero hunger and sustainable agriculture (SDG 2) and health and well-being (SDG 3). Environmental aspects include industry, innovation and infrastructure (SDG 9), climate change (SDG 13), and life on land (SDG 15). Social aspects include quality education (SDG 4) and responsible consumption and production (SDG 12). The relationship between squares and questions is summarized in Table 2.

The TLS were developed based on the findings from various journal articles and book that integrate concepts related to the application of edible coatings on fruits and vegetables. The TLS derived from a comprehensive literature review, established connections between each section and identified relationships within the grid structure from squares A1 to D9. The sequences were validated by five experts, who affirmed their suitability for educational activities. Minor revisions were recommended by the validators. The methodology for producing and characterizing edible coatings was modified to be more general due to the wide range of possible ingredients. Enhancements were made to concepts related to biopolymer classification and postharvest technology. Additionally, the components of each section were reorganized for improved clarity and comprehension.

Table 2. Questions on the TLS

Relationship between Squares	Question
A1 and A2	What causes fruit rot easily?
A2 and A3	What is the solution to this problem?
A3 and B4	What are the main raw materials that can be used to make edible coatings?
A3 and B5	What are the main raw materials that can be used to make edible coatings?
A3 and B6	What are the types of additives for making edible coatings?
A3 and C7	How to make and what are the characterization tests for edible coatings?
A3 and C8	How is the application technique for applying edible coating to fruits?
A3 and D9	How is the potential of edible coating in supporting sustainable living?

Each element within the section in TLS possesses the potential for implementation through the Project-based Learning model (PjBL). In the last ten years, PjBL has been widely researched to improve the science process in science learning (Napitupulu et al., 2024). The syntax of PjBL includes fundamental questions, project design, project implementation, and project communication (Dwiningsih & Aisy, 2024). Each syntax encompasses one section in the TLS, including the basic question syntax contained in section one, designing the project in section 2, implementing the project in section 3, and communicating the project results in section four. One application of this TLS is in the development of digital teaching materials focused on sustainable lifestyles, integrated with Ethnographic Project-based Learning (Ethno-PjBL) (Daulay & Asrizal, 2024)

Conclusion

This study uses qualitative content analysis as a research method to develop TLS. The results of this research are as follows: TLS divided into four sections, postharvest losses, edible coating materials, preparation and characterization of edible coatings, and potential edible coatings to support sustainable living based on SDG-related points Zero Hunger (SDG 2), Good Health and Well-Being (SDG 3), Quality Education (SDG 4), Industry, Innovation, and Infrastructure (SDG 9), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), and Life on Land (SDG 15). The validation confirmed that the TLS content is appropriate for chemistry learning. The results of the TLS in this study can be adapted to develop learning designs or teaching materials with ESD content in the context of edible coatings for vegetables and fruits.

Acknowledgments
The author extends gratitude to two of the author's academic supervisors for helping the author in compiling this article and three experts in polymer materials and the context of edible coatings for their willingness to be a validator in this research.

Author Contributions
Conceptualization, D. S.; methodology, D. S.; validation, H. H. and A. S.; formal analysis, A. F. and A. A.; investigation, D. S.; A. F. and A. A; resources, H. H. and A. S.; data curation, D. S.; A. F. and A. A; writing—original draft preparation, D. S.; A. F. and A. A; writing—review and editing, D. S.; A. F. and A. A; visualization, and D. S. and A. F.; All authors have read and agreed to the published version of the manuscript.

Funding
This research received no external funding.

Conflicts of Interest
The authors declare no conflict of interest.

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