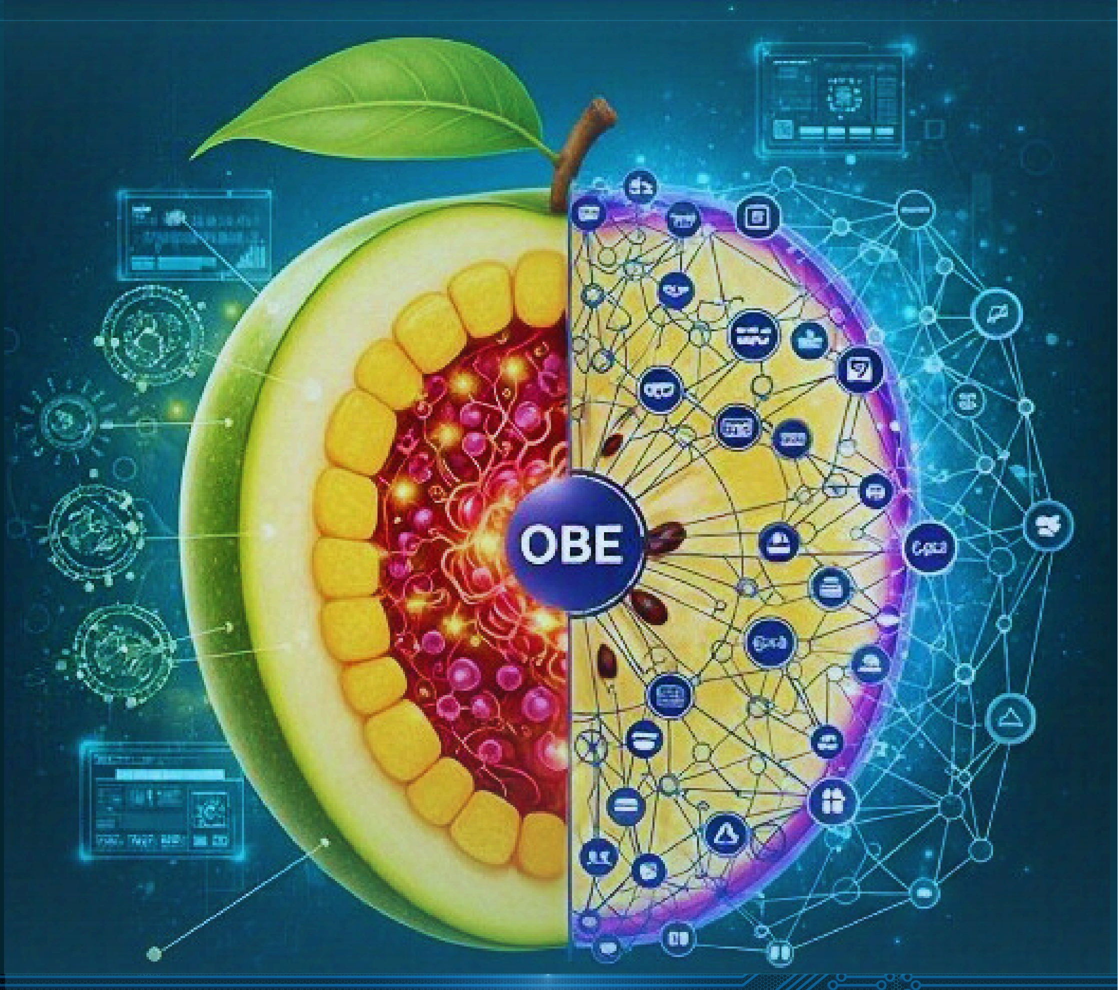
MAWADRA LESTARI ENTERPRISE

POSTHARVEST PHYSIOLOGY AND TECHNOLOGY BASED ON OBE

PROF. DR. IR. I KETUT BUDARAGA, MSI. CIRR



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Written by :

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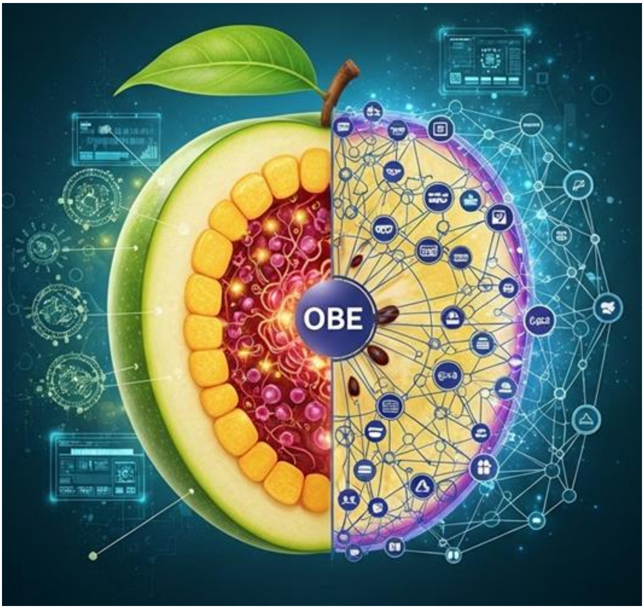

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Preface

PREFACE

Praise be to God Almighty, who has bestowed His grace and blessings, so that the writing of this book entitled OBE-Based Postharvest Physiology and Technology can be completed well.

Postharvest is a crucial part of the food supply chain, where product quality is significantly influenced by physiological processes, environmental factors, and the application of appropriate technology. Therefore, mastering the concepts of postharvest physiology and related technologies is crucial not only for students but also for practitioners and researchers working in the agriculture and food sector. This book aims to bridge the gap between theory and practice, emphasizing the interconnectedness of basic science, the application of modern technology, and innovations based on local wisdom.

The Outcome-Based Education (OBE) approach used in developing the materials aims to ensure that the learning process emphasizes not only knowledge acquisition but also the development of analytical and creative skills and professional attitudes needed to face real-world challenges. Through the integration of theory, case studies, projects, and practice, students are expected to understand post-harvest issues holistically and offer innovative and applicable solutions.

This book still has many shortcomings. Therefore, we greatly appreciate criticism and suggestions for its further improvement and perfection. We extend our gratitude to the various parties who have assisted in the completion of this book. We hope this book can serve as a reference source and easy-to-understand literature.

Mawadra Lestari Enterprise

CHAPTER 1
Introduction

Postharvest physiology and technology play a crucial role in maintaining the quality, nutritional value, and shelf life of agricultural products, making understanding this area a fundamental requirement in agricultural higher education. Common problems that frequently arise during the postharvest stage, such as physiological damage, yield loss, and quality degradation, not only cause economic losses but also impact food availability. Therefore, postharvest learning needs to be designed with an approach that integrates theory and practice, one of which is through the concept of Outcome-Based Education (OBE) emphasizes learning outcomes in the form of knowledge, skills, and attitudes relevant to the needs of the workplace. By linking post-harvest physiology and technology to the OBE framework, students are not only equipped with scientific understanding but also guided to formulate innovative solutions that directly contribute to reducing yield losses and strengthening sustainable food security.

1.1 Background Importance of Postharvest Physiology and Technology

Postharvest physiology and technology is a crucial field in agricultural science that focuses on understanding the biological, physiological, and biochemical changes in horticultural products after harvest. Agricultural products such as fruits, vegetables, tubers, and seeds are living materials that continue to undergo metabolic processes even after being separated from the parent plant. These physiological activities include respiration, transpiration, and aging, which contribute to product quality degradation. Without proper management, agricultural products will quickly experience physical, physiological, and microbiological deterioration, reducing their market value and impacting public food access (Kader & Yahia, 2020). Therefore, understanding postharvest physiology is the foundation for designing technologies that can maintain product quality and extend their shelf life.

The most common post-harvest problem in developing countries is high yield loss. Losses can reach 20–50% depending on the commodity type, handling technology, and storage conditions. Contributing factors include mechanical damage due to improper handling, uncontrolled temperature and humidity, and post-harvest pathogen attacks. These losses not only impact farmers economically but also lead to inefficiencies in resources used during production, such as water, fertilizer, and energy. Therefore, knowledge of post-harvest physiology must be integrated with the application of modern technology to significantly reduce yield losses (Kitinoja & AlHassan, 2021).

Besides yield loss, another challenge faced in post-harvest handling is the decline in organoleptic qualities, such as color, texture, aroma, and flavor, which significantly influence consumer preferences. These qualities are closely related to the product's internal metabolic processes, such as the breakdown of starch into sugar in ripe fruit or tissue softening due to cell wall degradation. Without proper physiological control, these processes can continue until they cause total damage. Therefore, post-harvest technology based on an understanding of product physiology is crucial for maintaining freshness and increasing the market value of agricultural commodities.

In the context of education, mastery of post-harvest physiology and technology is not sufficient merely in theory, it needs to be implemented in practical learning that is relevant to the needs of the food industry. Outcome-Based Education (OBE) offers a suitable framework because it emphasizes the achievement of tangible competencies in the form of knowledge, skills, and attitudes. Through OBE, students are expected to understand the physiological mechanisms underlying post-harvest damage and design technology-based solutions to mitigate these problems. Thus, OBE-based post-harvest learning can equip students with the analytical and innovation skills needed in the workplace.

The application of OBE in postharvest physiology and technology learning provides a significant opportunity to develop students' critical thinking skills. Within this framework, students are not only asked to understand the theories of respiration, transpiration, or the role of ethylene in ripening, but also to examine real-life cases such as tropical fruit damage during distribution. The learning process is directed at student-centered learning that encourages students to actively identify, analyze, and solve problems. This approach is expected to increase the relevance of postharvest science to the demands of national and global food security.

The relevance of post-harvest physiology and technology to food security is inseparable. Food security is determined not only by the quantity of production at the farm level, but also by the availability of quality food that can be distributed to consumers. If post-harvest losses cannot be controlled, food availability will decrease even if production at the upstream level is sufficient. Therefore, understanding post-harvest physiology is a crucial pillar in strengthening food security because it can support supply chain efficiency, reduce waste, and increase product added value.

The importance of post-harvest physiology and technology also lies in their linkage with locally-based innovation. Many natural ingredients, such as essential oils, plant extracts, and liquid smoke, can be used to extend the shelf life of products. The use of simple technologies like evaporative cooling or biopolymer-based eco-friendly packaging demonstrates that physiology can be combined with local wisdom to create practical and sustainable solutions. This also demonstrates that the integration of scientific knowledge, modern technology, and local resources can support more resilient agricultural development.

Thus, the importance of post-harvest physiology and technology extends beyond the technical aspects of product quality control to social, economic, and sustainability dimensions. Mastering this knowledge through the OBE approach will produce graduates who not only master theoretical concepts but also apply this knowledge in real-world practice to address post-harvest issues. Through OBE-based education, it is hoped that a competent and innovative generation will emerge to support efforts to improve the quality of agricultural products and strengthen national food security.

1.2 Common Post-Harvest Problems of Agricultural Products

Common post-harvest problems in agricultural products are essentially related to product quantity and quality losses that occur from harvest through handling, storage, distribution, and finally reaching consumers. Quantitative losses occur in the form of weight, volume, or marketable product quantity, while quality losses are characterized by decreased nutritional value, freshness, and consumer acceptance. In developing countries, post-harvest yield losses can reach 30–50 percent, depending on the commodity and environmental conditions. This problem not only harms farmers economically, but also reduces food availability and increases vulnerability to national food security (Affognon et al., 2015).

Mechanical damage is a dominant factor causing post-harvest losses. Substandard harvesting, transportation, and distribution processes can cause bruising, cracks, or splits in fruits and vegetables. This mechanical damage accelerates respiration and transpiration, opens the way for microbial infection, and accelerates the decay process. This suggests that an understanding of post-harvest product physiology must be accompanied by the application of appropriate harvesting and handling technologies, such as the use of ergonomic harvesting containers, transportation systems that reduce shock, and temperature control during distribution (Elik et al., 2019).

In addition to physical damage, physiological factors are also a significant issue in post-harvest handling. Horticultural products continue to undergo metabolic processes after harvest, so high respiration rates can accelerate aging and quality decline. Climacteric fruits such as bananas, mangoes, and tomatoes exhibit a sharp increase in respiration rates and ethylene production after harvest, which results in accelerated ripening and reduced shelf life. Without adequate control, these fruits will quickly deteriorate and lose their market value.

Another problem that has a big impact is water loss through transpiration. Water loss causes wilting, decreased firmness, and significant weight loss in produce. Environmental factors such as high temperature, low humidity, and excessive air circulation accelerate this transpiration process. For example, leafy vegetables like lettuce, spinach, or kale are highly susceptible to water loss, which can lead to a loss of freshness within hours. Therefore, rapid cooling technology, controlled-humidity packaging, and the use of natural protective coatings are solutions that need to be developed.

Microbial infections are a major problem that exacerbates post-harvest deterioration. Pathogens such as fungi, bacteria, and molds thrive in horticultural products with high moisture content and vulnerable tissues. The resulting damage not only reduces organoleptic quality but can also pose health risks due to mycotoxins. Predisposing factors such as mechanical injury, high humidity, and poor sanitation accelerate the spread of pathogens. Therefore, post-harvest control must include good sanitation practices, antimicrobial treatments, and packaging technologies that inhibit the growth of microorganisms.

Inefficient distribution and supply chains contribute to post-harvest problems. Limited storage and transportation infrastructure in many regions means agricultural products must travel long distances without adequate refrigeration facilities. As a result, products arrive at the market damaged or with a very short shelf life. This problem is often encountered in tropical horticultural commodities that require a cold chain from harvest to consumer. The absence of a cold chain system is one of the main causes of high post-harvest losses in developing countries.

In addition to technical factors, socioeconomic aspects also contribute to high post-harvest losses. Farmers' limited knowledge of harvest standards, limited access to storage technology, and minimal training in post-harvest handling are serious obstacles. Unequal infrastructure and access to technology mean that most farmers still use traditional, inefficient methods. This emphasizes that solutions to post-harvest problems are not solely technical but also require a sustainable educational and empowerment approach.

Post-harvest issues also impact the environment. Large amounts of wasted produce generate greenhouse gas emissions from decomposition, increase the burden of organic waste, and waste natural resources used for production. Therefore, post-harvest issues are not only about food efficiency but also related to environmental sustainability. Efforts to reduce post-harvest losses also contribute to climate change mitigation and more prudent resource use.

These issues collectively demonstrate that postharvest physiology and technology must be viewed as integral parts of a sustainable food system. A thorough understanding of the physiological, mechanical, microbiological, and environmental factors influencing postharvest damage is fundamental to designing effective technologies and management strategies. Integrating science, modern technology, and socioeconomic approaches is necessary to minimize postharvest losses, improve farmer welfare, and strengthen global food security (Elik et al., 2019, Gustavsson & Stage, 2017).

1.3 Basic Concepts of OBE in Applied Science Learning

Post-harvest issues in agricultural products are one of the main challenges in the global food system, especially in developing countries that still face limitations in infrastructure, technology, and practical knowledge in crop management. Post-harvest yield losses can reach 30–50 percent in highly perishable horticultural commodities, such as fruits and vegetables, due to improper handling from harvest to distribution. Environmental factors such as temperature, humidity, and light exposure also play a major role in accelerating the process of quality degradation and causing significant economic and nutritional losses. This condition emphasizes that post-harvest problems cannot be viewed as merely a technical issue, but also impact food security and farmer welfare.

Physiological damage to agricultural products is often a major cause of post-harvest losses, especially for commodities that are highly sensitive to environmental changes. Fruits and vegetables, for example, undergo intensive respiration and transpiration after harvest, which, if uncontrolled, can lead to wilting, changes in texture, and decreased nutritional content. Post-harvest metabolic processes that occur without technological controls have the potential to accelerate spoilage, thereby reducing shelf life. This situation is exacerbated by a lack of understanding among farmers and supply chain actors regarding the physiological aspects of agricultural products, which leads to errors in storage and distribution.

Mechanical problems such as bruising, splitting, or injury to crops are also a major factor contributing to high post-harvest losses. Physical damage often occurs due to improper harvesting techniques, the use of inappropriate tools, or poor transportation conditions. These mechanical injuries not only deteriorate the product's appearance but also accelerate microbial contamination, leading to further deterioration. In a commercial context, visibly damaged produce generally has a low market value, even if it still contains good nutritional value, resulting in significant economic losses for farmers.

Post-harvest issues are also related to the limited storage technology available to farmers and small traders. Traditional storage systems, still widely used, fail to control temperature, humidity, and air circulation, which are crucial factors in maintaining product quality. Limited access to modern refrigeration technology is a major cause of agricultural losses in tropical countries. Furthermore, the lack of cold chain facilities makes it difficult to distribute fresh produce over long distances without significant quality degradation.

Another obstacle arises from the packaging aspect, which is often not adequately addressed by small and medium-sized businesses. The use of inappropriate packaging materials, such as sacks or open containers, can accelerate product deterioration due to the lack of protection against mechanical stress and environmental changes. However, appropriate packaging technology can slow down the physiological processes of the product and protect it from external contamination. Limited knowledge and investment costs often hinder the implementation of effective packaging technology at the farmer level.

The distribution of agricultural products from producers to consumers also faces serious transportation and logistics challenges. Long distribution channels, a lack of refrigerated transportation facilities, and poor road infrastructure exacerbate post-harvest losses. Fresh produce that should reach consumers promptly often experiences delays, reducing its quality. This directly impacts the competitiveness of local agricultural products, especially when competing with imported products with better supply chains.

Biological factors such as attacks by pathogenic microorganisms, fungi, and bacteria also pose a major threat to post-harvest agricultural products. Pathogenic infections in fruits and vegetables are often difficult to control without adequate preservation technology. The high humidity and hot temperatures of tropical regions accelerate the spread of microorganisms that cause spoilage. Without technological intervention, these biological attacks not only degrade product quality but can also pose health risks to consumers.

Furthermore, social and economic factors exacerbate post-harvest problems. Limited access to information, low technological literacy, and weak coordination between supply chain actors result in many agricultural products being mishandled. Farmers are often trapped in a system of quick sales at low prices due to limited storage and transportation facilities, leaving them with little bargaining power in the market. This creates a difficult-to-break cycle, where post-harvest losses continue and farmers' well-being remains stagnant.

These common post-harvest problems demonstrate the need for a holistic approach that integrates aspects of physiology, technology, supply chain management, and real-world needs-based education. The application of the post-harvest learning is relevant for equipping students with practical skills and innovative solutions to address real-world problems. With a solid understanding of agricultural product physiology, storage technology, and distribution management, young people can play a role in reducing yield losses, increasing local agricultural competitiveness, and strengthening national food security (Affognon et al., 2015, Kitinoja & Thompson, 2019, Yusuf et al., 2021).

1.4 Relevance of Postharvest Physiology and Technology to Food Security

The relevance of post-harvest physiology and technology to food security lies in their ability to maintain the quality and quantity of agricultural products produced by farmers. Globally, agricultural yield losses due to physiological damage and inadequate post-harvest treatment remain the primary causes of declining food availability. Post-harvest physiology enables an understanding of the biochemical changes, respiration, and transpiration of horticultural products, which significantly impact shelf life. With this understanding, storage and packaging technologies can be appropriately designed to significantly reduce yield losses, thus optimizing agricultural productivity to support community food availability.

Post-harvest technology is not only limited to extending shelf life but also plays a role in maintaining nutritional content, aroma, taste, and texture, which are important factors in consumer acceptance. Products that are damaged or lose quality post-harvest will reduce their selling value and worsen the condition of the food supply chain. Therefore, the success of post-harvest physiology and technology in maintaining the quality of agricultural products is directly linked to sustainable food security. The application of storage technologies based on controlled temperature, controlled atmosphere, and smart packaging technologies are innovations that can reduce food losses and increase distribution efficiency.

Food security concerns not only the physical availability of food but also the accessibility and stability of supply throughout the year. In this regard, post-harvest technology is a crucial tool for maintaining food supply continuity through preservation strategies, long-term storage, and minimal processing. For example, seasonal horticultural crops can remain available outside the harvest season thanks to cold storage and controlled atmosphere technologies that slow product respiration. Thus, post-harvest physiology and technology are fundamental to ensuring consistent food stability throughout the year, both for local needs and export markets.

The application of post-harvest physiology and technology also contributes to the reduction of food loss. This is a problem that occurs in various developing countries, including Indonesia. Post-harvest food losses often exceed 30 percent in horticultural commodities, causing economic losses and reducing food availability for the community. With appropriate strategies, such as humidity control, rapid cooling, or the use of packaging based on active materials, the rate of deterioration can be significantly reduced. This confirms that post-harvest physiology is not merely a technical issue but also a key strategy in supporting national and global food security (FAO, 2021).

Beyond technical aspects, the relevance of post-harvest physiology and technology to food security also relates to environmental and sustainability issues. Environmentally friendly post-harvest technologies, such as the use of biodegradable packaging or energy-efficient refrigeration technology, not only extend the shelf life of products but also reduce negative impacts on ecosystems. This approach aligns with the sustainable development agenda, which emphasizes providing sufficient, safe, and nutritious food for all levels of society without harming the environment. Therefore, the application of efficient and sustainable post-harvest technologies supports food security in both ecological and socio-economic dimensions.

The integration of post-harvest technology with food security also encompasses the added value dimension of agricultural products. Fresh produce can be increased in economic value through minimal processing, simple processing, or product differentiation based on local innovation. This way, farmers not only avoid losses due to quality degradation but can also generate greater profits through marketing value-added products. This strategy ultimately strengthens the competitiveness of agricultural commodities while expanding public access to quality products, thereby supporting food security from an economic and affordability perspective.

In the educational context, mastery of post-harvest physiology and technology is a crucial aspect in equipping students with skills relevant to the real challenges of the agricultural sector. Through this approach, Outcome-Based Education (OBE), students not only understand basic concepts but are also trained to design and implement innovative solutions to address post-harvest food loss. OBE-based learning establishes food security as a strategic goal that can be achieved through the application of applied science, technological skills, and multidisciplinary understanding (Biggs & Tang, 2022). Thus, the link between post-harvest physiology and food security also serves as a means to produce competent human resources.

Ultimately, the relevance of postharvest physiology and technology to food security can be understood as a comprehensive relationship between science, technology, and societal needs. Efforts to reduce agricultural losses, maintain food quality, increase added value, and support sustainable food systems are goals that can only be achieved through synergy between postharvest physiology, technological innovation, and food policies that support public welfare. Strong food security depends not only on the magnitude of on-farm production but also on how those products are effectively managed, stored, and distributed, supported by postharvest physiology and technology (Kader, 2020).

CHAPTER 2
Outcome-Based Education (Obe) Concept In Postharvest

Outcome-Based Education (OBE) is an educational approach that focuses on achieving competencies that must be possessed by graduates through the formulation of clear, measurable, and relevant learning outcomes to the needs of society and the world of work, so that in the context of the postharvest physiology and technology course, the application of OBE ensures that students not only understand the theory but are also able to apply it in solving real problems in the postharvest field. Graduate Learning Outcomes (CPL) in the postharvest field are directed at the formation of analytical skills, technical skills, and mastery of physiological concepts and agricultural product processing technology in order to support food security and product competitiveness. Furthermore, the learning outcomes of the postharvest physiology and technology course (CPMK) are focused on understanding the physiological processes of agricultural products, mastery of storage, packaging, and preservation technology, and the application of applied science-based innovations in postharvest practices. The relationship between CPL, CPMK, sub-CPMK, and assessment must be designed systematically so that each element is integrated in forming comprehensive student competencies, where CPL becomes the general direction, CPMK as the specific course outcomes, sub-CPMK as the details of specific skills or knowledge, and assessment as a measuring tool for learning success. To realize this, learning designs based on student-centered learning, problem-based learning, and project-based learning are very relevant to be implemented because they are able to place students as the center of learning, encourage real problem solving, and produce innovative projects that are directly related to actual issues in post-harvest.

2.1 Definition of OBE and its Basic Principles

Outcome-Based Education (OBE) is defined as an educational approach that emphasizes the achievement of measurable and targeted learning outcomes in accordance with the expected graduate profile, where every element of the curriculum, learning strategies, and evaluations are designed to ensure that students achieve the formulated learning outcomes. This definition emphasizes that educational success is not only determined by the delivery of material, but rather by the extent to which students are able to demonstrate competencies in accordance with established standards, both in terms of knowledge, skills, and attitudes. In the context of higher education in agriculture, OBE enables the integration of the needs of the world of work, developments in applied science, and relevance to strategic issues such as supply chain efficiency and reducing post-harvest losses.

The fundamental principle of OBE is centered on the idea that every student has the potential to learn and achieve specific competencies if given the appropriate opportunities and support. This principle emphasizes outcomes-oriented learning planning, integration between curriculum and assessment, and flexibility in learning methods to adapt to student needs. Thus, OBE not only assesses final results but also ensures a structured and systematic learning process to help students develop their abilities optimally. In the field of post-harvest physiology and technology, this principle is relevant because students are expected to connect the theory of agricultural physiology with the application of effective processing technology.

Principle of OBE emphasizes that learning objectives must be clear and measurable from the outset of planning, so that lecturers and students share the same direction in the learning process. This is crucial in post-harvest education because mastery of physiological concepts, agricultural product handling methods, and storage and processing technologies must be formulated specifically so that students can master them at a certain level. This clarity of objectives also allows lecturers to select appropriate learning strategies and design evaluations consistent with the expected learning outcomes.

In addition to clarity of purpose, OBE also emphasizes the principle of design down, deliver up, namely, curriculum planning begins with the graduate profile and desired learning outcomes, then breaks down into course outcomes, sub-outcomes, and learning strategies. With this approach, all educational elements are directed toward supporting the achievement of a graduate profile that aligns with the needs of the work field and scientific developments. In post-harvest education, this approach helps ensure that students acquire not only theoretical knowledge but also practical skills in managing post-harvest agricultural products efficiently and sustainably.

Principle of high expectations is also a key aspect of OBE is the belief that every student can achieve high standards if given adequate opportunity and support. This requires challenging yet realistic learning designs, along with facilities, mentoring, and formative evaluations that help students develop. In the post-harvest field, the application of this principle encourages students to identify real-world problems, develop innovative solutions, and boldly conduct experiments and research that support the reduction of agricultural losses.

Principle of expanded opportunity emphasizes that students need diverse opportunities to achieve desired learning outcomes, including through a variety of learning methods, the use of technology, and the application of problem-based and project-based approaches. In postharvest physiology and technology learning, these opportunities can be realized through practical activities, field research, case studies, and collaboration with the food industry. The broader the opportunities provided, the greater the opportunity for students to develop their competencies comprehensively.

The implementation of OBE also emphasizes the importance of integration between curriculum, learning, and assessment, where assessment serves not only to measure achievement but also as an integral part of the learning process. Assessment in OBE encompasses cognitive, psychomotor, and affective aspects, so students are assessed not only on their ability to memorize theory but also on their technical skills and demonstrated professional attitudes. In post-harvest education, this means students are assessed on their understanding of agricultural physiology, skills in applying storage technology, and ethics in maintaining food quality.

OBE also requires lecturers to act as facilitators, guiding, motivating, and providing meaningful learning experiences for students. The lecturer's role is no longer limited to conveying information, but rather as a mentor, ensuring students have the opportunity to explore, practice, and innovate. In the post-harvest context, lecturers must be able to present real-world challenges in the form of case studies of agricultural damage, supply chain simulations, and simple technology development projects relevant to local needs.

The implementation of OBE in agricultural higher education is ultimately aimed at producing graduates who are not only academically competent but also relevant to the needs of society and industry. With core principles emphasizing clarity of purpose, design integration, high expectations, and diverse learning opportunities, OBE is a suitable approach to improving the quality of postharvest physiology and technology instruction. This aligns with global demands for education that is oriented toward tangible outcomes, not merely processes, thus supporting the achievement of food security and sustainable development (Biggs & Tang, 2022, Harden & Crosby, 2020, Thirumalesh & Krishnamurthy, 2021).

2.2 Graduate Learning Outcomes (CPL) in the Postharvest Sector

Graduate Learning Outcomes (CPL) in postharvest agriculture are an important foundation in formulating the competency profile that students must possess upon completing higher education in this field. CPL is designed to ensure that graduates not only understand the theoretical concepts of postharvest physiology and technology but also are able to apply this knowledge in real-world contexts.

Within the Outcome-Based Education (OBE) framework, CPL refers to the ability to think critically, solve problems, and possess technical skills in maintaining the quality, safety, and sustainability of agricultural products after harvest. Therefore, CPL in this field encompasses the domains of knowledge, skills, and attitudes that mutually support each other in addressing global challenges in food security and technological innovation.

One highly relevant CPL is the ability of graduates to identify and analyze common post-harvest problems, such as yield loss, quality degradation, and food safety. This skill requires students to master the basics of agricultural product physiology, understand the factors that accelerate deterioration, and master technological strategies for storage, packaging, and minimal processing. Thus, graduates are expected to contribute to minimizing food loss and waste, which are critical issues in the global agricultural sector (Kusnandar & Dewi, 2021).

In addition to analytical skills, the CPL in postharvest also emphasizes mastery of practical skills through laboratory and field-based learning. Graduates must be able to apply postharvest physiological measurement methods, utilize modern storage technology equipment, and develop simple, locally-based innovations tailored to farmer and market conditions. Acquiring these skills will strengthen graduates' capacity to connect basic science with practical needs in the field, thereby enhancing agricultural products' shelf life and increasing their economic value.

CPL also encompasses soft skills, including communication, collaboration, and leadership within multidisciplinary teams. In the post-harvest context, graduates often collaborate with farmers, entrepreneurs, regulators, and researchers, making interpersonal skills essential. Graduates are not only required to convey ideas clearly but also to guide communities in adopting environmentally friendly and sustainable post-harvest technologies. This aligns with higher education policy, which integrates technical aspects with social skills to ensure graduates are globally competitive (Yuliana, 2020).

At the attitude learning achievement level, postharvest graduates are expected to possess ethical awareness and responsibility for food sustainability and the socio-economic impacts of technology implementation. Students need to be equipped with an understanding of the importance of maintaining a balance between technological efficiency and the sustainability of agricultural ecosystems. These ethical values are crucial in the modern era, where issues of climate change, resource constraints, and food security are increasingly complex. Graduates with high integrity will be better prepared to face the dilemmas of implementing postharvest technology in society.

The CPL in postharvest also emphasizes research and innovation skills. Graduates are expected to conduct simple and applied research oriented towards solving immediate postharvest problems. For example, research on natural preservation methods to replace hazardous chemicals or biodegradable packaging innovations to reduce plastic waste. These skills will strengthen graduates' contribution to promoting a healthier and more sustainable food system. By mastering research methodology, graduates can also continue their education to a higher level and enrich their knowledge of postharvest science.

Global and entrepreneurial learning outcomes are also crucial. Postharvest graduates are not only expected to work in the public or academic sectors, but also to become entrepreneurs who create innovative products from local agricultural produce. This competency aligns with modern market needs, which demand product diversification based on postharvest technology, such as minimally processed products, functional foods, or environmentally friendly industrial raw materials. With the right CPL (Cultivation of Postharvest Management) qualifications, graduates are able to develop innovation-based businesses, thereby strengthening the local economy (Saragih & Pambudi, 2022).

Linking CPL to the needs of the agricultural industry is also a priority in curriculum development. Today's workforce demands professionals who not only understand technical aspects but also adapt to digital technology developments in post-harvest management. For example, the use of smart sensors, the Internet of Things (IoT), and big data to monitor the storage conditions of agricultural products. Therefore, CPL in the post-harvest field must be aligned with Industry 4.0 trends to ensure graduates are more adaptable and relevant to current developments.

Overall, the postharvest physiology and technology program is designed to produce graduates who are academically competent, technically skilled, ethical in decision-making, innovative in research, and adaptive to market and technological needs. The implementation of this CPL serves as a benchmark for the success of OBE-based education, as every learning activity is directed toward achieving the final outcome of graduates who are ready to face real-world challenges in the postharvest sector. Thus, education in postharvest physiology and technology is not only oriented towards knowledge transfer, but also towards the development of high-quality human resources that are relevant to global challenges.

2.3 Course Learning Outcomes (CPMK) Postharvest Physiology & Technology

The Postharvest Physiology and Technology Course Learning Outcomes (CPMK) are designed to provide students with comprehensive competencies to understand the physiological mechanisms that occur in agricultural products after harvest and apply appropriate technology to maintain their quality. This understanding emphasizes not only theoretical aspects but also practical skills that support innovation in postharvest product management. In the context of OBE-based education, CPMK emphasizes students' ability to connect physiological concepts with the application of appropriate technology so as to reduce agricultural yield losses while increasing product competitiveness in the global market.

A key component of the CPMK program includes mastering the concepts of post-harvest physiological changes such as respiration, transpiration, and biochemical degradation that affect the freshness and shelf life of agricultural products. Students are expected to be able to identify real-world problems in different commodities, such as fruits, vegetables, and grains, and then analyze the factors causing deterioration. This mastery forms the basis for developing skills in designing storage and distribution strategies that suit the physiological characteristics of each product. This way, students not only learn theory but also understand the practical context relevant to the needs of the modern agricultural industry.

The next focus of CPMK is skills in applying post-harvest technologies aimed at reducing yield losses and improving quality. Technologies such as cold storage, modified packaging, the use of natural preservatives, and the application of digital sensors to monitor agricultural product quality are essential components of the learning process. According to Singh and Langowski (2022), mastery of post-harvest technology must be integrated with an understanding of product physiology for optimal effectiveness. Therefore, students are encouraged to combine biological aspects with technological engineering.

In addition to technical skills, CPMK also emphasizes critical analysis in evaluating various post-harvest processing methods. Students are expected to assess the advantages and limitations of each technology, both from a technical, economic, and sustainability perspective. This process aligns with the principles of OBE-based learning, which requires students to possess applied evaluative and problem-solving skills. This is crucial because post-harvest challenges are not only technical but also related to environmental issues, food security, and supply chain efficiency.

Scientific communication skills are also part of the CPMK, designed to equip students to communicate analytical results, both in academic reports and professional presentations. In the post-harvest context, students need to be able to convey findings on agricultural product handling strategies to various stakeholders, from farmers and industry players to consumers. According to Biggs and Tang (2022), communication skills are a crucial aspect of learning outcomes because they serve as a bridge between theory, practice, and implementation in the field.

The integration of ethical and sustainability aspects is also emphasized in the Postharvest Physiology and Technology CPMK. Students are expected to be aware that the technology chosen must align with environmentally friendly principles and contribute to long-term food security. This includes understanding the impacts of chemical use, energy savings in storage, and optimizing the use of postharvest waste. This approach aligns with global trends emphasizing the importance of sustainable food systems to address the challenges of climate change and population growth.

Within the OBE framework, the Postharvest Physiology and Technology CPMK is also directed at fostering collaborative skills.

Students not only work individually but are also trained to work in interdisciplinary teams involving the fields of physiology, food technology, logistics, and agricultural economics. This collaboration is expected to produce more comprehensive and innovative solutions for postharvest agricultural product handling. Thus, students can understand that success in maintaining agricultural product quality cannot be achieved with a single approach, but through the integration of various disciplines.

A further achievement in CPMK is the ability to develop research-based innovations. Students are directed to conduct small research projects or applied projects related to post-harvest issues, such as developing new packaging techniques or applying digital technology to product freshness monitoring. According to Zizka et al. (2020), research-based experiences in OBE education enhance students' ability to innovate and adapt to changing industry needs. Thus, CPMK not only produces graduates competent in basic knowledge but also prepared to face new challenges in the post-harvest sector.

Ultimately, the Postharvest Physiology and Technology CPMK is designed to produce graduates with competitive advantages and high relevance in the workforce. Mastery of physiology, technology application skills, analytical skills, communication, collaboration, and research innovation combine to equip students to contribute significantly to improving the efficiency of the postharvest chain. With an OBE-based design, each learning outcome is directed toward developing a graduate profile capable of addressing global challenges in providing quality, safe, and sustainable food.

2.4 Relationship between CPL – CPMK – Sub CPMK – Assessment

The relationship between graduate learning outcomes, course learning outcomes, sub-course learning outcomes, and assessments forms a systematic chain that forms an OBE-based learning framework. Graduate learning outcomes are designed to represent the general competencies a graduate must possess, while course learning outcomes serve as specific derivatives that support the achievement of these competencies. Sub-course learning outcomes then detail more measurable capabilities in the form of knowledge, skills, and attitudes that can be directly assessed. This hierarchical relationship ensures that the learning process is not merely conceptual, but also measurable and directed towards tangible outcomes that align with the needs of the workplace.

The interrelationship between CPL, CPMK, and sub-CPMK requires clarity in the formulation of each outcome so that it can be translated into a valid and reliable assessment instrument. For example, if CPL targets graduates to be able to manage post-harvest to maintain food quality, then CPMK should emphasize understanding the principles of post-harvest physiology and technological skills in handling it. Sub-CPMK can then focus on technical skills such as measuring respiration rate, evaluating freshness quality, or designing storage systems based on commodity needs. This aligns with the view that each stage of achievement must be observable through clear performance indicators (Biggs & Tang, 2022).

Assessment serves as a verification instrument to determine whether the specified sub-CPMK are truly achieved. Therefore, assessment design must be directly linked to learning outcome indicators. Assessments are not limited to written exams but can also include practicums, case studies, projects, or portfolios. Authentic assessment is crucial because it provides a concrete picture of students' ability to apply theory to practical problems in the post-harvest sector. Within the OBE framework, assessments oriented toward the learning process and product are essential to ensuring the quality of outcomes (Spady, 2020).

The relationship between CPL, CPMK, sub-CPMK, and assessment also illustrates the existence of a sustainable cycle in education. Assessments are conducted not only to measure achievement but also to provide feedback for improving curriculum design and learning methods. For example, if it is discovered that a majority of students have not mastered cold storage techniques, improvements to the teaching approach or the addition of practical work are necessary. Thus, the OBE system is not static, but rather dynamic, adapting to evolving graduate competency needs (Zubaidah et al., 2021).

In the context of postharvest physiology and technology, the integration of CPL, CPMK, and sub-CPMK can be directed towards a balanced mastery of scientific and applied aspects. CPL can focus on mastering the principles of food sustainability, CPMK on physiological process analysis skills, and sub-CPMK on technical skills in measuring quality parameters. Assessments are then designed to test understanding, laboratory skills, and the ability to design innovative solutions to real-world problems. With this structure, students not only understand the concepts but are also prepared to face real-world challenges in the food industry.

The interconnectedness of learning outcomes and assessment also creates opportunities for the application of various innovative learning strategies. For example, problem-based learning can be directed toward achieving the Core Competency (CPMK) related to post-harvest physiology problem-solving, while project-based learning can support the sub-CPMK, namely the skill of designing storage technology. Project assessment then serves as a means of validating students' achievement. In this way, the integration of CPL, CPMK, sub-CPMK, and assessment becomes more meaningful because it is contextualized to the real world.

The development of outcomes and assessments within the OBE framework must also consider sustainability and global relevance. Post-harvest issues relate not only to production efficiency but also to food safety, waste reduction, and climate change adaptation. Therefore, the CPL (Cultivation of Post-Harvest) should encompass ethical and sustainability aspects, the CPMK (Environmental Impact Analysis) should include environmental impact analysis skills, and sub-CPMKs can be directed toward evaluating environmentally friendly practices. Sustainability project-based assessments can be a means to assess students' understanding of these issues in a professional context.

Thus, the relationship between CPL, CPMK, sub-CPMK, and assessment creates a structured, measurable, and relevant educational framework that meets the needs of industry and society. Each stage of achievement, broken down into more operational forms, ensures that postharvest physiology and technology education does not stop at the theoretical level but produces graduates with real competencies. Assessment serves as both a measuring tool and a means of continuous improvement, ensuring graduates are truly capable of contributing to maintaining food security and the sustainability of the agricultural sector.

2.5 Learning Design: Student-Centered Learning, Problem-Based Learning, Project-Based Learning

The learning design within the OBE framework for the post-harvest physiology and technology course must place students at the center of learning activities. Student-centered learning provides opportunities for students to be more active in constructing knowledge through exploration, discussion, and reflection. In this context, lecturers act as facilitators, guiding students in finding answers to real-world post-harvest problems, rather than simply transferring information. This allows students to develop independent learning and critical thinking skills, essential for addressing the complexity of issues in the food sector (Weimer, 2013).

The first sub-chapter can be directed at the application of student-centered learning in understanding post-harvest physiology, for example through literature studies on the respiration process of fruits and vegetables and group discussions to compare the results of recent research. This activity allows students to build deeper experiential knowledge while simultaneously practicing academic communication skills. The implementation of this strategy ensures that learning outcomes relate not only to cognitive aspects but also to the complementary affective and psychomotor aspects.

Besides that, Problem-Based Learning (PBL) can be a highly relevant learning design because post-harvest problems always arise in complex forms that require multidisciplinary analysis. Students can be presented with case scenarios, such as crop loss due to spoilage or microbial contamination, and then asked to identify the root cause, find supporting data, and formulate applicable solutions. With this approach, students not only understand the concepts of post-harvest physiology but also learn to apply their knowledge in real-world situations to solve practical problems (Hmelo-Silver, 2019).

The application of PBL in post-harvest learning can also strengthen collaborative skills. Students are encouraged to work in heterogeneous teams to complement each other's knowledge and skills. This collaboration provides simulated experience of real-world work practices in the food industry, where problem-solving is typically accomplished through teamwork. Thus, the CPL aspect, which emphasizes collaboration and professional communication skills, can be optimally achieved.

In the next sub-chapter, project-based learning (PjBL) is an effective learning strategy for integrating theoretical concepts and practical applications. Students can be tasked with designing innovation-based post-harvest storage or processing systems, such as environmentally friendly packaging technology or the use of digital sensors to monitor commodity quality. These projects require students to conduct small-scale research, collect data, analyze results, and prepare scientific reports, thus developing both academic and professional skills in a balanced manner.

PjBL in postharvest physiology and technology courses is also relevant for developing creative and innovative thinking skills. Students are not only required to understand existing technologies but are also guided to generate new ideas that meet the needs of industry and society. This aligns with the OBE objective, which emphasizes outputs in the form of tangible, immediately applicable competencies, including the ability to innovate in solving food and sustainability challenges (Larmer et al., 2015).

The integration of these three approaches, namely student-centered learning, PBL, and PjBL provide students with a more holistic learning experience. Students acquire not only declarative knowledge but also procedural and metacognitive skills. By combining these three strategies, students can learn actively, collaboratively, and productively, producing work. This makes the learning design more aligned with the characteristics of OBE, which prioritizes end-results in tangible competencies and performance.

Assessment of learning designs based on these three strategies must be authentic and integrated with learning outcomes. Assessments can include observations of discussion processes, the quality of project reports, presentations, and individual reflections. This assessment approach is crucial to ensure that learning outcomes are measured not only by written exam results but also by students' analytical, creative, collaborative, and communicative skills. This ensures a consistent connection between CPL, CPMK, sub-CPMK, and assessment.

Ultimately, learning design is based on student-centered learning, PBL, and PjBL in postharvest physiology and technology courses can produce graduates who not only master theory but also possess applied, adaptive, and innovative skills. With these skills, graduates can contribute to addressing real-world issues in the food sector, particularly in the postharvest stage, which is crucial for the quality, safety, and sustainability of agricultural products. This aligns with the OBE's goal of achieving comprehensive graduate competencies.

CHAPTER 3
Basics Of Postharvest Physiology

The basics of postharvest physiology are an important foundation in understanding how agricultural products such as fruits, vegetables, tubers, and seeds undergo changes from harvest to consumption, because each commodity has a structure and composition that affect its shelf life. Key physiological processes such as respiration and transpiration determine the rate of quality decline, where high respiration activity accelerates the degradation of energy reserves while transpiration triggers water loss resulting in weight loss and decreased freshness. In addition, the aging process or*senescence*and the role of ethylene in ripening is often a critical factor that accelerates product deterioration, so it is necessary to understand it in depth to design control technology. Physiological and biochemical damage that occurs after harvest, such as*chilling injury*or pigment oxidation, poses a serious challenge in maintaining the quality of agricultural products. To support OBE-based learning outcomes, students need to analyze the differences in respiration rates between climacteric and non-climacteric fruit through case studies. This allows them to not only understand theoretical concepts but also relate them to applicable post-harvest handling strategies relevant to industry needs.

3.1 Structure and Composition of Agricultural Products (Fruits, Vegetables, Tubers, Seeds)

The structure and composition of agricultural products are key factors determining their quality, shelf life, and post-harvest processing potential. Fruits, vegetables, tubers, and seeds have different tissue structures, including cellulose, hemicellulose, lignin, and water content, which influence their physical durability. Fruits generally have thinner cell walls and higher water content than seeds or tubers, making them more susceptible to mechanical and microbiological damage. These structural differences have significant implications for post-harvest technology design, such as selecting appropriate storage methods for each commodity.

The chemical composition of agricultural products is also highly diverse, ranging from carbohydrates, proteins, lipids, vitamins, minerals, to phytochemicals with biological activity. Fruits are typically rich in simple sugars and vitamin C, while leafy vegetables contain chlorophyll, fiber, and essential minerals. Tubers are the primary source of starch, while seeds contain significant amounts of reserve protein and fat. These compositional variations determine both nutritional potential and susceptibility to post-harvest biochemical degradation. Therefore, understanding composition is fundamental to preservation strategies.

In fruits and vegetables, the high water content makes them highly susceptible to physiological changes after harvest. Continued enzyme activity causes respiration and transpiration, which accelerate tissue degradation. Phenolic compounds and pigments such as anthocyanins and carotenoids also play a role in determining the color and appearance of the product, so their degradation is often used as an indicator of freshness. Therefore, chemical composition is not only a nutritional aspect but also a visual quality indicator.

Tubers have a complex starch storage structure, with starch granules that are relatively stable under low temperature conditions, but can undergo retrogradation when processed or stored for too long. In addition, the water content of tubers varies depending on the species, which also determines their texture and shelf life. The change in starch composition to simple sugars in cold storage, such as in potatoes, often causes problems of excessive sweetness and browning when fried. This shows the importance of understanding the storage physiology of each commodity.

Seeds, as agricultural products with low moisture content, tend to be more stable during long-term storage. Their high content of globulin proteins, albumin, and unsaturated fats makes them highly valuable as a food source and industrial raw material. However, seeds are also susceptible to lipid oxidation and insect attack if storage conditions are not controlled. Maintaining a balanced moisture content is crucial, as seeds with too high a moisture content can experience germination or mold growth.

Physiologically, differences in cell wall structure and energy reserve composition influence respiration rates between commodities. Climacteric fruits with high starch content, such as bananas and mangoes, experience a surge in respiration after harvest, while seeds remain more stable. These differences have implications for storage atmosphere control strategies tailored to the characteristics of each product.

Furthermore, structure and composition also determine resistance to mechanical treatments such as sorting, washing, and packaging. Soft-fleshed fruits like tomatoes are easily damaged by pressure, while grains are more resistant to such treatments. Understanding these physical characteristics is fundamental to supply chain design focused on reducing post-harvest losses.

Biochemical factors such as oxidative enzyme content also need to be considered. Polyphenol oxidase enzymes in fruits and vegetables can trigger enzymatic browning, thereby reducing organoleptic quality. Different enzyme compositions in each commodity require specific post-harvest treatments, such as the use of low temperatures or oxidation inhibitors. Therefore, structure and composition become integrative factors between physiology, biochemistry, and processing technology.

In the context of OBE-based education, understanding the structure and composition of agricultural products can be a specific learning outcome. Students are expected to not only understand the theory but also be able to identify commodity characteristics through compositional analysis labs, microscopic structural observations, and case studies of products stored under different conditions. Thus, the competencies developed are applicable and relevant to the real-world challenges of modern post-harvest management (Kader, 2020, Kitinoja & Thompson, 2019, Yahia & Carrillo-López, 2018).

3.2 Respiration and Its Effect on Shelf Life

Respiration is a key physiological process that continues continuously after harvest and has a significant impact on the shelf life of agricultural products. Respiration rates vary across commodities, depending on the variety, ripeness level, and storage conditions. Climacteric fruits such as bananas, mangoes, and tomatoes experience a sharp increase in respiration rates after harvest, followed by rapid ripening and quality decline. Conversely, non-climacteric fruits such as oranges and grapes have more stable respiration rates, resulting in longer shelf life. This difference is an important basis for determining effective post-harvest handling strategies.

The energy produced by respiration is necessary to maintain cellular metabolism, but the consequence is the loss of energy reserve substrates such as starch, sugar, or organic acids. This loss contributes to a decline in nutritional and organoleptic quality, for example, the decrease in sugar content in fruit that has been stored for too long. Furthermore, increased respiration accelerates heat production and increases water loss through transpiration. The combination of these two factors accelerates wilting in leafy vegetables and accelerates decay in soft-fleshed fruits.

Storage conditions such as temperature, humidity, and oxygen availability significantly influence respiration rates. Low temperatures have been shown to effectively slow the activity of respiratory enzymes, thereby extending the shelf life of most horticultural products. However, storage at excessively low temperatures can cause chilling injury in tropical commodities such as papaya or bananas, which actually deteriorates quality. Adjusting the storage atmosphere by lowering oxygen levels and increasing carbon dioxide levels has also been widely used to inhibit respiration without damaging cell structure.

Differences in respiration rates between commodities are also closely related to texture and water content. Green leafy vegetables like spinach and lettuce have very high respiration rates, requiring rapid cooling immediately after harvest. Tubers like potatoes or cassava have lower respiration rates but still experience changes in chemical composition due to enzymatic activity. Therefore, storage strategies must consider the specific characteristics of each commodity.

Besides affecting shelf life, respiration is also linked to the formation of volatile compounds that determine a product's aroma and flavor. In climacteric fruits, increased respiration is accompanied by ethylene accumulation, which accelerates ripening and triggers changes in color, aroma, and texture. The use of ethylene inhibitors such as 1-methylcyclopropene (1-MCP) has been shown to slow this process in apples, bananas, and mangoes, extending shelf life without compromising sensory quality.

Respiration control is also a focus of modern post-harvest technology innovation. Controlled atmosphere (CA) and modified atmosphere packaging (MAP) technologies allow for the regulation of gas concentrations around produce to slow metabolism. For fresh vegetables, MAP uses permeable packaging that allows for a natural gas balance. This technique has been shown to double the shelf life of fresh vegetables compared to conventional storage, while maintaining organoleptic quality.

Internal physiological factors such as ripeness also significantly influence respiration rates. Fruit harvested overripe generally has a high respiration rate, leading to rapid quality decline. Conversely, harvesting at the correct physiological ripeness stage allows the product to withstand transportation and storage better. Therefore, understanding respiration dynamics based on ripeness is crucial for post-harvest management.

In the context of OBE-based learning, understanding respiration and its impact on shelf life can be considered an essential competency. Students need to be trained to analyze differences in respiration rates between commodities, measure respiration activity through laboratory experiments, and assess the effect of storage conditions on product quality. With this approach, students not only understand the theoretical aspects but also master the practical skills needed to design efficient post-harvest strategies tailored to commodity needs (Kitinoja & Thompson, 2019, Yahia & Carrillo-López, 2018, Wills et al., 2016).

3.3 Transpiration and Water Loss

Transpiration is an important physiological process in fresh agricultural produce associated with water loss through the skin surface, lenticels, and stomata, thus significantly determining the shelf life and quality of the product. Excessive water loss can cause weight loss, wilting, shrinkage, and decreased sales value, especially in horticultural commodities with high water content. Transpiration rates vary depending on the type of commodity, physiological age, and storage conditions, so understanding the transpiration mechanism is fundamental to developing appropriate post-harvest technology. Internal factors such as epidermal structure, cuticle thickness, and stomatal distribution significantly influence transpiration rates, which require in-depth study in the context of post-harvest management.

Transpiration rate is also influenced by external factors, particularly temperature, relative humidity, and airflow velocity around the product. Storage at low relative humidity accelerates water loss, while excessively high humidity can promote microbial growth. Therefore, a balance of environmental conditions is key to reducing transpiration damage. Recent studies have shown that significantly lowering storage temperature can slow transpiration rates by reducing the kinetic energy of water molecules and suppressing the vapor pressure gradient (Thompson, 2021). Therefore, cold storage technology not only inhibits respiration but also plays a crucial role in reducing water loss in agricultural products.

The most visible physiological impact of transpiration is a decrease in cell turgor, which causes a loss of freshness in produce. In leafy vegetables, water loss of just 5–10 percent is enough to significantly reduce commercial quality. Meanwhile, in fruits, symptoms such as wrinkled skin or shrunken flesh can reduce consumer preference. Furthermore, uncontrolled transpiration can increase the concentration of solutes in tissues, potentially accelerating the physiological aging process. Understanding this is highly relevant to supporting OBE-based learning, as students not only understand the theory but are also able to relate it to real-world quality issues.

Various post-harvest technologies have been developed to reduce transpiration rates, including the use of packaging with controlled permeability, edible coatings, and modified atmospheres. Edible coatings, for example, can form a semi-permeable layer that reduces water evaporation without disrupting gas exchange essential for respiration. Meanwhile, modified atmosphere plastic packaging can create more stable micro-humidity conditions around the product, thereby reducing water loss. This technology has proven effective in extending the freshness of various horticultural commodities such as tomatoes, chilies, and mangoes (Elik et al., 2019).

Using storage spaces with controlled humidity is also a key strategy for reducing water loss. In refrigerated storage, relative humidity is maintained at 85–95 percent to prevent product dehydration. However, excessively high humidity should be avoided as it can cause condensation, which can support mold growth. Therefore, humidifier technology and controlled air circulation systems are integral to modern warehouse design. By combining temperature and humidity control, transpiration rates can be significantly reduced without increasing the risk of microbial contamination.

In addition to technology, a physiological approach through harvesting at optimal maturity also plays a crucial role. Products harvested too young are typically more susceptible to water loss due to their immature tissue structure, while products that are too old tend to experience more rapid tissue degradation. Therefore, an understanding of transpiration physiology must be integrated with agronomic practices and proper harvest timing. This approach aligns with outcome-based learning, where students are guided to master analytical and applied competencies in post-harvest quality management.

The implementation of technological innovations oriented towards transpiration reduction not only impacts product quality but also the efficiency of the agricultural supply chain. Minimizing water loss means reducing weight loss, which is directly related to the economic value of the product. On a large scale, transpiration control strategies contribute to reducing food loss, a global issue. According to the FAO (2021), post-harvest yield losses due to dehydration still account for a significant percentage of total horticultural supply chain losses, making managing transpiration physiology a fundamental aspect of maintaining food security.

Thus, discussions of transpiration and water loss are not only important in the context of post-harvest physiology but also serve as strategic teaching materials in an OBE-based curriculum. Students can be guided to conduct direct experiments to measure transpiration rates in various commodities and assess the effectiveness of control technologies. This approach fosters critical thinking skills, problem-solving skills, and technological mastery relevant to the needs of the food industry. By integrating theory, practice, and technological application, graduates' competency in managing the quality of post-harvest agricultural products can be significantly improved.

3.4 Aging Process (Senescence)

The aging process, or senescence, in agricultural products is the final stage of physiological development characterized by decreased metabolic function, cell degradation, and reduced tissue integrity, ultimately leading to a decline in product quality. Senescence is triggered by internal factors such as the physiological age of cells and hormonal balance, as well as external factors such as temperature, humidity, and exposure to certain gases. In fruits and vegetables, senescence is characterized by color changes, tissue softening, loss of freshness, and the appearance of textural damage, which leads to decreased consumer appeal. This phenomenon is important to study in the post-harvest context because it is directly related to the shelf life and economic value of agricultural products (Kader, 2020).

Biochemical changes that occur during senescence involve the degradation of pigments such as chlorophyll, the accumulation of carotenoid and anthocyanin pigments, and changes in cell wall structure, resulting in a softer texture. Protein and cell membrane degradation also triggers ion leakage and increases susceptibility to microbial attack. The activity of hydrolytic enzymes such as pectinase, cellulase, and protease plays a significant role in accelerating the decline in the physical and nutritional quality of the product. This process occurs naturally but can be accelerated by suboptimal storage conditions, making appropriate post-harvest handling strategies crucial to reducing the rate of senescence (Ali et al., 2021).

Hormonal factors significantly influence the mechanism of senescence, particularly the role of ethylene as the primary trigger hormone. Ethylene accelerates the expression of genes associated with cell wall degradation, increased respiration, and the synthesis of hydrolytic enzymes. In climacteric fruits, ethylene production increases sharply before and during ripening, thus accelerating senescence. Conversely, in non-climacteric fruits, the influence of ethylene is relatively lower, although it still plays a role in modulating the aging process. Regulation of other hormones, such as abscisic acid, cytokinins, and gibberellins, also contributes to senescence dynamics through complex interactions within cellular metabolic pathways (Wills et al., 2021).

One important implication of senescence is the loss of essential nutrients, particularly vitamins and bioactive compounds beneficial to health. For example, vitamin C in fruits and vegetables is easily degraded due to increased oxidative activity during the aging process. Furthermore, senescence also triggers increased activity of oxidative enzymes such as polyphenol oxidase (PPO), which causes enzymatic browning of tissues. This reduces the visual appeal and nutritional value of produce, posing a significant challenge in maintaining the quality of fresh food on the market (Kader, 2020).

Senescence control strategies in post-harvest handling generally involve manipulating storage conditions, such as low temperature, high relative humidity, and the use of modified or controlled atmospheres. Cold storage technology has been shown to slow metabolic rates, suppress ethylene production, and delay senescence. However, inappropriate low-temperature treatment can cause chilling injury in certain commodities, requiring tailored approaches to the physiological characteristics of each product. Therefore, a thorough understanding of post-harvest physiological characteristics is fundamental to designing effective storage technologies (Ali et al., 2021).

In addition to physical factors, chemical and biological approaches are also applied to control senescence. The use of ethylene-inhibiting compounds such as 1-methylcyclopropene (1-MCP) has been shown to be effective in extending fruit shelf life by inhibiting ethylene binding to cell receptors. Treatment with growth-regulating hormones such as cytokinins can delay chlorophyll degradation and prolong leaf freshness. Meanwhile, biological approaches such as the application of certain probiotics are beginning to be investigated to slow tissue degradation and suppress pathogen infections during the senescence phase (Wills et al., 2021).

The implications of senescence extend beyond economic losses due to declining product quality to impact the food supply chain. High post-harvest losses due to senescence contribute to global food loss, particularly in developing countries with limited storage technology. Therefore, understanding and managing senescence is a crucial component of Outcome-Based Education (OBE)-based post-harvest physiology and technology courses, equipping students with analytical and solution-oriented skills to address real-world agricultural problems (Ali et al., 2021).

In the context of OBE-based learning, the study of senescence can be used as a case study to connect physiological theory with the application of post-harvest handling technology. Students are encouraged to analyze the factors causing senescence in various commodities, design simple experiments to measure the rate of quality decline, and evaluate the effectiveness of applied control technologies. With this approach, students not only understand the theoretical concept of senescence but also develop skills in formulating practical solutions relevant to the needs of the horticulture and sustainable agriculture industries.

3.5 The Role of Ethylene in Product Ripening and Deterioration

Sub-chapters on the role of ethylene in ripening and product damage can be developed through brainstorming into several main aspects such as the mechanism of ethylene biosynthesis and regulation, the effect of ethylene on ripening of climacteric and non-climacteric fruits, the interaction of ethylene with other hormones in regulating senescence, the role of ethylene in reducing the quality and accelerating the damage of horticultural products, ethylene control technology in the supply chain, the application of ethylene inhibitors such as 1-methylcyclopropene (1-MCP), storage strategies to reduce ethylene accumulation, and case studies on the application of ethylene control in extending the shelf life of agricultural products.

Ethylene is a key plant hormone that regulates fruit ripening, the aging process, and responses to abiotic and biotic stress. Physiologically, ethylene is produced through the methionine biosynthesis pathway, with the primary precursor S-adenosylmethionine (SAM), which is converted to 1-aminocyclopropane-1-carboxylate (ACC), which is ultimately converted to ethylene by the enzyme ACC oxidase. Increased activity of this enzyme is typically triggered by specific physiological conditions, such as the climacteric phase in fruit, characterized by a surge in respiration. Therefore, a thorough understanding of the regulation of ethylene biosynthesis is key to controlling ripening and slowing the quality degradation of agricultural products (Kou et al., 2021).

Climacteric fruits such as bananas, tomatoes, and mangoes exhibit a high dependence on ethylene for ripening, while non-climacteric fruits such as grapes and oranges exhibit a more ethylene-independent ripening pattern. However, even though non-climacteric fruits do not experience a significant surge in respiration, ethylene still plays a role in inducing certain physiological changes such as chlorophyll degradation or tissue softening. Understanding these differences in response is important in the context of postharvest physiology, as postharvest storage and handling strategies must be tailored to the physiological characteristics of each commodity (Mitra, 2020).

Besides its role in ripening, ethylene also accelerates senescence in plant tissues, including leafy vegetables, cut flowers, and germinating seeds. The senescence process is characterized by pigment degradation, loss of turgor, and decreased metabolic activity. Ethylene's interaction with other hormones, such as abscisic acid and gibberellins, also accelerates physiological deterioration. In a post-harvest context, accelerated senescence caused by ethylene poses a major challenge because it reduces shelf life, accelerates textural deterioration, and reduces the nutritional value of the product (Saltveit, 2019).

Ethylene control technology has advanced rapidly, including the use of 1-methylcyclopropene (1-MCP), which works by binding to ethylene receptors on cell membranes, thereby inhibiting ethylene signal perception. The application of 1-MCP has been shown to be effective in extending the shelf life of climacteric fruits such as apples, pears, and tomatoes by inhibiting ripening and maintaining sensory quality. Furthermore, the use of potassium permanganate-based ethylene absorbers or activated carbon in storage spaces is also widely applied to reduce ethylene concentrations in the storage atmosphere (Kou et al., 2021).

Controlled atmosphere storage strategies such as Controlled Atmosphere (CA) and Modified Atmosphere Packaging (MAP) also contribute to reducing ethylene accumulation. Reducing oxygen levels and increasing carbon dioxide levels can suppress ethylene biosynthesis and slow respiration. This approach is particularly effective for ethylene-sensitive commodities, making the integration of gas-controlled packaging technologies a crucial component of cold chain management.

The negative impact of ethylene on agricultural product quality is not only seen in accelerated ripening, but also in physiological damage such as chilling injury, increased susceptibility to pathogens, and decreased texture and flavor. For example, in leafy vegetables like lettuce and spinach, ethylene exposure accelerates the onset of "russet spotting," a symptom that reduces the product's market value. This reinforces the urgency of integrated ethylene management to ensure a sustainable supply of high-quality fresh produce.

From an OBE perspective, students' understanding of the role of ethylene extends beyond physiological concepts to its application in designing effective storage strategies. Through a problem-based learning approach, students can analyze real-world cases, such as differences in post-harvest treatment between climacteric and non-climacteric fruit, and propose appropriate ethylene control technologies. Thus, learning outcomes can be more measurable in the form of analytical and application skills that align with the demands of the workplace in post-harvest technology.

3.6 Postharvest Physiological and Biochemical Damage

Postharvest physiological and biochemical damage is a complex process that occurs in agricultural products due to the interaction of internal and external factors that affect product quality. Physiologically, damage can occur as a result of environmental stress such as extreme temperatures, low humidity, or inappropriate storage conditions. For example, fruit stored at temperatures below its physiological threshold can experience chilling injury, characterized by brown spots, loss of aroma, and abnormal texture. This factor indicates that each commodity has a unique physiological threshold, making knowledge of its characteristics crucial in postharvest systems (Kays & Paull, 2020).

From a biochemical perspective, postharvest damage is often associated with uncontrolled changes in cellular metabolism. These changes include increased activity of cell wall-degrading enzymes such as polygalacturonase and cellulase, which accelerate tissue softening, and oxidation of phenolic compounds, which causes browning. These biochemical changes not only reduce sensory quality but also impact the nutritional value of the product. This makes controlling postharvest biochemical processes a crucial aspect in extending shelf life (Zhang et al., 2021).

Physiological damage can also be associated with impaired intercellular water and nutrient transport. Excessive dehydration of horticultural produce not only loses mass but also triggers structural changes in the plasma membrane, making cells more susceptible to oxidative damage. These changes are often seen in leafy vegetables that wilt rapidly after harvest, suggesting that uncontrolled transpiration exacerbates physiological damage. Therefore, managing relative humidity in storage spaces is an important strategy to mitigate these impacts.

Furthermore, physiological and biochemical factors often interact to determine the extent of damage. For example, improper cooling can trigger the accumulation of free radicals in tissues, which further damage lipid membranes through peroxidation. This membrane damage then accelerates the loss of cellular compartments, increasing oxidative enzyme activity and exacerbating product degradation. Such interactions illustrate the multidimensional nature of postharvest damage, with physiological and biochemical aspects inseparable.

In the context of spoilage control, postharvest technology plays a crucial role in suppressing physiological and biochemical changes. Techniques such as controlled atmosphere storage and the use of edible coatings have proven effective in delaying spoilage by reducing respiration rates, reducing water loss, and inhibiting oxidative enzyme activity. These technologies directly slow the tissue degradation process, thus maintaining product quality for longer. This strategy aligns with the principles of postharvest physiology, which seeks to maintain metabolic balance at a minimum level.

It's also worth noting that physiological and biochemical damage have significant implications for food security and economic value. Damaged products throughout the supply chain not only reduce farmers' and traders' profits but also increase food waste. Therefore, a thorough understanding of physiological and biochemical mechanisms is crucial for designing effective technology-based interventions. This underscores the importance of integrating postharvest physiology into Outcome-Based Education (OBE) curricula, enabling students to connect theory with real-world practice.

On the other hand, genetic factors also determine a commodity's susceptibility to post-harvest damage. Certain varieties have higher natural antioxidant content, making them more resistant to oxidative damage, while others are more susceptible to physiological changes such as chilling injury. Plant breeding focused on post-harvest resilience is one long-term solution to reduce physiological and biochemical damage to agricultural products. This innovation can strengthen post-harvest strategies based on modern technology.

Thus, analyzing postharvest physiological and biochemical damage not only provides theoretical understanding but also forms the basis for developing practical solutions for quality management. Through a multidisciplinary approach combining physiology, biochemistry, storage technology, and supply management, postharvest losses can be significantly reduced. This approach also enriches the OBE-based learning dimension by enabling students to explore real-world problems, analyze their causes, and develop innovative, applicable solutions (Wills et al., 2021).

3.7 OBE Case Study: Analysis of Differences in Respiration Rates of Climacteric vs. Non-Climacteric Fruits

Learning Objectives (Learning Outcomes)

After completing this case study and questions, students are expected to be able to:

A. CLO 1: Analyze the differences in physiological characteristics between climacteric and non-climacteric fruits, particularly regarding respiration rate and ethylene production.
B. CLO 2: Apply scientific methods to measure and compare respiration rates in different fruit samples.
C. CLO 3: Evaluating the physiological implications of respiration rate on post-harvest handling and storage of fruit.

Case Study: Optimizing Post-Harvest Handling of Local Fruit at Maju Makmur Supermarket

Maju Makmur Supermarket (PSMM) is once again facing challenges. Despite implementing several initial recommendations, losses due to fruit damage remain significant, particularly for local fruits such as butter avocado, fragrant sweet mango, and Cavendish banana. This damage occurs not only during storage in the store but also during transportation and distribution from production centers. PSMM Manager, Mr. Andy, recognized the need for a more scientific and integrated approach, combining physiology and post-harvest technology.

Mr. Andy commissioned a team of university researchers to conduct an in-depth analysis. The team developed a more comprehensive experimental plan:

A. Sampling: Samples were taken from several locations: directly from farmers, upon arrival at the PSMM warehouse, and on display shelves. Each sample was categorized as climacteric (avocado, mango, banana) or non-climacteric (orange, strawberry, grape) fruits.
B. Measurement of Physiological Parameters: The team measured the respiration rate (CO_2produced per unit mass per hour) and ethylene production (C_2H_4produced) using a gas chromatograph and respirometer. Measurements were taken every 12 hours for 7 days at controlled temperature and humidity.
C. Visual Quality Observation: The team also recorded physical changes such as color, hardness, texture, and aroma to correlate physiological data with the visual condition of the fruit.
D. Storage Simulation: Fruits were stored under various simulated conditions:
    1. Room temperature (25°C)
    2. Cold temperature (5°C)
    3. Controlled atmosphere (CA) with concentrations of oxygen (O_2) and carbon dioxide (CO_2) which is regulated.

The results are very clear. Climacteric fruits show a bell-shaped respiration rate curve (climacteric spike) that coincides with a spike in ethylene production. This increase accelerates ripening and subsequent spoilage. In contrast, non-climacteric fruit shows a stable and low respiration rate, without ethylene spikes, resulting in a longer shelf life.

Further analysis showed that high temperatures and ethylene exposure from other climacteric fruits (e.g., ripe bananas) significantly accelerated the deterioration of surrounding unripe climacteric fruit, a phenomenon that frequently occurs during transportation and storage in the PSMM warehouse. These findings provided the basis for the research team to formulate specific and measurable technological recommendations.

For each sample, they measured respiration rates and ethylene production over 7 days of storage at room temperature. The results showed that fruit from Group A experienced a significant spike in respiration rates and ethylene production, followed by rapid ripening and eventual decay. In contrast, fruit from Group B exhibited relatively stable respiration rates throughout the observation period and did not undergo further ripening after picking.

These findings strengthen the expert team's hypothesis that understanding fruit physiology is key to addressing the problem of losses in PSMM.

OBE Based Questions

Question 1 (CLO 1: Postharvest Physiology Analysis and Evaluation)

Based on the data found by the research team in the case study, draw and explain the respiration rate and ethylene production curves for mangoes (climacteric) and citrus fruits (non-climacteric) over a 7-day storage period. Analyze why these physiological dynamics (surges in respiration and ethylene in mangoes, and steady rates in citrus) fundamentally affect the shelf life and post-harvest handling strategies for both fruits.

Question 2 (CLO 2: Application of Measurement Methods and Techniques)

Design two different practical methods to accelerate and slow down the ripening of bananas (climacteric).

A. Part A (Speeding Up):Describe one method that utilizes the principles of fruit physiology to accelerate banana ripening. List the tools, materials, and biochemical mechanisms behind the method.
B. Part B (Slowing Down):Describe one post-harvest technology method that can be used to slow the respiration rate and ripening of bananas during storage. Explain how it works, the parameters that need to be adjusted, and how it can be applied in the PSMM warehouse.

Question 3 (CLO 3: Formulating Solutions and Technology Recommendations)

You are a member of a research team assigned to prepare a final report for Mr. Budi. Develop three specific and measurable post-harvest technology recommendations to address losses in PSMM. Each recommendation should:

A. Focuses on utilizing the understanding of respiration rates and ethylene production.
B. Briefly explain how the technology works.
C. Provides examples of practical implementation in a PSMM environment (e.g., warehouse, display racks).

Question 4 (CLO 4: Critical Thinking and Complex Problem Analysis)

Mr. Budi proposes storing all types of fruit in one large cold room at 5°C to save costs. Critically analyze this proposal. Discuss the potential benefits and risks of this approach, considering the physiological differences between climacteric and non-climacteric fruits. Why is a 'one temperature fits all' strategy not ideal for post-harvest handling? Explain at least two potential negative impacts.

CHAPTER 4
Factors Affecting Post-Harvest Quality

Postharvest agricultural product quality reflects a complex interaction between internal and external factors. Internal factors, including genetics, morphological structure, and chemical composition, determine a product's inherent quality potential. For example, certain fruit varieties are genetically more durable, while sugar or starch content influences flavor and texture. However, this potential cannot be fully realized without managing external factors such as temperature, humidity, and gas composition, which are key to controlling the rate of postharvest physiological deterioration. The interaction between the environment and product physiology determines how quickly the product undergoes quality deterioration. A thorough understanding of these relationships allows us to identify relevant quality indicators and implement appropriate postharvest technologies to maintain the quality of agricultural products from harvest to consumer.

3.1 Internal Factors: Genetics, Morphological Structure, Chemical Content

Genetics plays a fundamental role in determining the initial quality potential of a horticultural product. Each variety, from apple to tomato, has a unique genetic code that controls critical traits such as respiration rate, ethylene sensitivity, and disease resistance (Kader, 2021). These traits essentially serve as a blueprint that determines how quickly the product will ripen, how long it can be stored, and how susceptible it is to quality deterioration. For example, the 'Gedong Gincu' mango variety has a genetic profile that leads to rapid ripening and high sugar content, while the 'Arumanis' variety may have a longer shelf life. By selecting the right varieties for specific post-harvest purposes, we can proactively manage product quality before any technological treatments are applied.

The morphological structure, or physical architecture of a product, is also a crucial internal factor. The outer skin, for example, acts as a natural protective barrier that minimizes water loss and prevents pathogens from entering. The presence of cuticular wax on apple skin or the thick peel of an orange are examples of morphological protection mechanisms. Conversely, fruits with thin, sensitive skins, such as strawberries or raspberries, are more susceptible to mechanical damage and water loss, which directly accelerates spoilage (Thompson & Sargent, 2020). Furthermore, the size and shape of a product can also influence how it is handled and packaged, ultimately affecting its overall quality.

More than appearance, chemical composition is a key determinant of a product's sensory quality, including flavor, aroma, and color. Components such as sugars, organic acids, and volatile compounds are central to the consumer's sensory experience. High sugar content in fruits like grapes and watermelon is a sought-after indicator of ripeness, while the balance between sugars and acids in citrus fruits determines freshness. During ripening, starch is converted to sugar, and organic acids can degrade, a process entirely controlled by the product's internal enzymatic activity (Al-Shibli, 2023).

The complex interactions between these internal factors determine the dynamics of postharvest physiology. For example, a variety with a genetic predisposition for high respiration rates (a genetic factor) will have more rapid chemical changes, especially if its morphological structure (a morphological factor) is susceptible to water loss. Morphological damage, such as bruising or small tears in the skin, can trigger stress reactions at the cellular level that release ethylene and accelerate the aging process. Understanding these interconnections is vital for designing effective postharvest strategies, from variety selection to cooling methods.

Modern approaches to postharvest science also include genetic modification to improve quality. Through genetic engineering or conventional breeding, researchers can develop new varieties with superior characteristics, such as longer shelf life, disease resistance, or even higher nutritional content. For example, the 'Flavr Savr' tomato, engineered to ripen later and have a firmer texture, demonstrates the potential of genetic engineering to address postharvest challenges.

In addition to taste and texture, the content of bioactive compounds such as vitamins, antioxidants, and phytochemicals is also integral to postharvest quality, especially from a nutritional and health perspective. These compounds tend to decline over storage time, and the rate of this decline is influenced by internal factors such as the genetic stability of the enzymes involved and the chemical composition of the product itself. The vitamin C content of oranges, for example, will gradually decline, and the rate of decline can be accelerated by improper storage temperatures.

Chemical component analysis is routinely used as an objective indicator of postharvest quality. Measurements such as total dissolved solids (TSS) with a refractometer, total acidity, and hardness with a penetrometer provide quantitative data that can be used to predict shelf life and verify quality. This data is crucial for industry to ensure that products delivered to market meet established quality standards, and for researchers to evaluate the effectiveness of postharvest treatments.

At a more microscopic level, morphological damage to produce can trigger a series of detrimental physiological reactions. When produce is bruised or injured, the integrity of cells and tissues is compromised, releasing enzymes such as polyphenol oxidase, which cause enzymatic browning. This process not only damages the visual appearance but can also create an entry point for microbial pathogens. Synergistic management of internal and external factors is key to minimizing this damage and maintaining post-harvest product quality.

3.1 External Factors: Temperature, Humidity, Light, Gas, Mechanical Treatment

Temperature is the most crucial external factor controlling metabolic rates, including respiration rates, in post-harvest produce. In general, every 10°C increase in temperature doubles the respiration rate, a principle known as Van't Hoff's rule or Q10 (Kader, 2021). High respiration rates directly accelerate ripening, aging, and quality deterioration because energy and nutrient reserves in produce are depleted more rapidly. Therefore, optimal temperature management, through processes such as pre-cooling and cold chain storage, is a key strategy for extending shelf life and maintaining product freshness. Each product has its own ideal storage temperature, and storage outside this range can lead to chilling injury or heat damage.

In addition to temperature, the relative humidity (RH) of the storage environment has a direct impact on the rate of water loss from produce. Most fresh fruits and vegetables have a very high water content, often above 90%. The difference in vapor pressure between the produce and the surrounding air is the primary driver of transpiration, or water loss. If the RH is too low, produce will rapidly wilt, shrivel, and lose weight, significantly reducing its marketability. Conversely, too high a RH can lead to water condensation on the surface of produce, creating ideal conditions for mold and bacterial growth (Al-Shibli, 2023). Therefore, maintaining an optimal RH level, typically between 90-95%, is key to minimizing water loss without encouraging microbial growth.

Light, though often overlooked in post-harvest handling, also affects some products. In products like potatoes, light exposure can trigger solanization, the formation of chlorophyll and glycoalkaloids (solanine), which cause a green color and bitter taste. On the other hand, light exposure can be used in certain products like tomatoes or citrus fruits to stimulate pigment synthesis (carotenoids and anthocyanins) to enhance visual appeal. However, excessive exposure to ultraviolet (UV) light can damage cells, trigger free radical production, and accelerate quality deterioration. Therefore, light management, especially for sensitive products, is a crucial part of any storage strategy.

The gas composition of the storage environment, particularly the concentrations of oxygen (O2), carbon dioxide (CO2), and ethylene (C2H4), has a strong effect on postharvest physiology. Controlled atmosphere (CA) and modified atmosphere packaging (MAP) are technologies that intentionally manipulate the concentrations of these gases. By decreasing O2 and increasing CO2, the respiration rate can be dramatically suppressed, thereby slowing ripening and senescence. Ethylene, known as the ripening hormone, can accelerate these processes even at very low concentrations, so its removal from the storage environment is key to extending the shelf life of climacteric fruits.

Mechanical processes such as harvesting, transport, and handling in the warehouse can cause various types of physical damage, such as bruising, abrasions, or tears. This damage not only impairs the visual appearance of the product but also triggers a series of physiological responses. Damaged tissue increases respiration, releases ethylene, and provides an entry point for spoilage-causing pathogens. Preventing mechanical damage through gentle handling protocols and the use of appropriate packaging are vital proactive measures for maintaining post-harvest quality (Thompson & Sargent, 2020).

The synergistic interaction between temperature and humidity is integral to cold chain operations. Cold temperatures can suppress respiration rates, but if not balanced with adequate humidity, products will dry out. Conversely, if humidity is too high at cold temperatures, condensation can occur, facilitating the growth of previously unseen mold and bacteria. Simultaneous temperature and humidity control is essential to creating an optimal storage environment for a variety of products.

Mechanical damage to produce is not only physical but also triggers complex physiological responses. When cellular tissue is damaged, separate enzymes within the cells can mix, triggering enzymatic browning reactions. Damaged cells also release volatile compounds that can trigger ripening in other produce nearby. Therefore, physical damage to one product can accelerate the domino effect of the entire lot.

Overall, a thorough understanding of these external factors forms the basis for the development and implementation of post-harvest technologies. From refrigeration and controlled atmosphere storage to the use of ethylene scrubber technology, all are based on physiological principles influenced by the external environment. Integrating all these factors into a unified system is key to maximizing shelf life, minimizing losses, and ultimately, ensuring the availability of safe, high-quality food for consumers.

4.3 Interaction of Environmental Factors with Post-Harvest Physiology

The post-harvest physiology of an agricultural product is not a static process, but rather a dynamic response to environmental conditions. Temperature, as the most dominant external factor, directly regulates respiration and transpiration rates, two key physiological processes that affect shelf life. Increasing temperature accelerates respiration, which consumes carbohydrate and nutrient reserves, thus accelerating product aging. Furthermore, high temperatures can also trigger the production of ethylene, a ripening hormone, in climacteric fruits, which in turn accelerates ripening and triggers quality decline (Kader, 2021). Technological treatments such as rapid cooling (pre-cooling) aim to disrupt this interaction, proactively slowing metabolic rates and extending shelf life.

The interaction between relative humidity (RH) and transpiration has a direct impact on turgor and product freshness. Turgor is the fluid pressure within cells that provides firmness to fruits and vegetables. When the RH in the storage environment is low, the vapor pressure gradient between the product and the air increases, causing water from the product to evaporate through the stomata and epidermis. This water loss not only reduces the weight of the product, which has economic implications, but also causes wilting and loss of texture. On the other hand, very high RH can cause condensation on the surface of the product, creating an ideal humid environment for mold and bacterial growth (Al-Shibli, 2023).

The gas composition surrounding produce is one of the environmental factors that can be effectively manipulated to control post-harvest physiology. The interaction between oxygen (O2), carbon dioxide (CO2), and ethylene (C2H4) is crucial, especially in climacteric fruits. With controlled atmosphere (CA) technology, O2 concentrations are lowered and CO_2 concentrations are increased, directly suppressing respiration rates and ethylene production. The ethylene produced by the fruit can be captured using absorbents, preventing it from triggering the ripening of other produce nearby. This manipulation of the gas environment allows produce to "sleep" and significantly extends its shelf life.

Mechanical treatments, such as bruising or abrasion, trigger a series of damaging physiological responses. This physical damage compromises cell and tissue integrity, leading to the release of enzymes that cause enzymatic browning and undesirable aromas. Physical wounds also act as entry points for pathogenic microorganisms, which exploit the nutrients leaked from damaged cells to multiply. Therefore, gentle, low-touch postharvest handling is essential to prevent these damaging interactions.

Temperature not only affects respiration rate but also interacts synergistically with ethylene. At high temperatures, the product's sensitivity to ethylene increases, resulting in a more rapid and intense ripening effect. For example, bananas stored at high temperatures and exposed to ethylene will ripen and spoil much more quickly than those stored at low temperatures. Understanding this interaction is the basis for the use of technologies such as cold storage with ethylene absorbers to control ripening.

Complex interactions between environmental factors also influence the rate of postharvest nutrient loss. For example, vitamin C, which is sensitive to temperature and oxygen, degrades more rapidly at high storage temperatures. Meanwhile, low temperatures, while slowing respiration, can cause degradation of carotenoid pigments in some products. Therefore, optimal postharvest strategies must consider how each environmental interaction will affect not only the physical quality but also the nutritional value of the product.

The primary role of postharvest technology is to manage adverse interactions between the environment and product physiology. These technologies act as intermediaries, manipulating environmental conditions to slow physiological processes that lead to quality degradation (Thompson & Sargent, 2020). For example, refrigeration technology controls temperature, humidity technology controls transpiration, and controlled atmosphere technology controls respiration and ethylene production. Without technological intervention, produce would rapidly deteriorate after harvest.

Ultimately, the interaction between environmental factors and postharvest physiology also determines a product's resistance to pathogens. Mechanical damage to produce caused by rough handling can make it susceptible to fungal or bacterial infections. Unfavorable environmental conditions, such as high humidity leading to condensation, can encourage the proliferation of pathogens present on the product's surface. By managing these environmental factors, we can minimize the chance of infection and safely extend the shelf life of produce.

4.4 Agricultural Product Quality Indicators

Postharvest agricultural product quality is not a single concept, but rather a multidimensional construct measured through a series of quality indicators. These indicators encompass physical, chemical, physiological, and microbiological aspects that collectively determine a product's value to consumers and industry. In general, quality indicators serve as objective benchmarks for evaluating the effectiveness of postharvest handling, predicting shelf life, and ensuring compliance with market standards. A comprehensive understanding of these indicators is essential for any practitioner in the field of postharvest physiology and technology.

One of the most common groups of quality indicators is physical indicators. These indicators are easily measurable and are often the first assessments consumers make. Examples of physical indicators include product size, shape, and weight, which affect uniformity and marketability. Product firmness or texture, measured with a penetrometer, is an important indicator of ripeness and freshness. Weight loss, primarily due to transpiration or evaporation, is a direct indicator of handling and storage efficiency. Additionally, physical defects such as bruises, cuts, or tears are also assessed because they can impair visual appearance and provide entry points for pathogens.

Chemical indicatorsprovides deeper insight into the internal composition of a product and is often directly related to flavor and nutrition. Total soluble solids (TSS), measured with a refractometer, is a primary indicator of sugar content and is often used to assess fruit ripeness. The balance between sugars and acids, measured by titration, is an important determinant of flavor profile. Other indicators include starch, vitamins (such as vitamin C), and bioactive compounds (such as antioxidants), all of which influence the nutritional value of the product (Al-Shibli, 2023). Chemical analysis is the basis for determining the optimal harvest time and evaluating quality degradation during storage.

Physiological indicatorsprovides an overview of the life processes occurring in the product after harvest. Respiration rate is a key indicator of metabolic activity, and its curve (climacteric or non-climacteric) forms the basis for storage strategies. Ethylene production levels, which can be measured using gas chromatography, are a key indicator of ripeness in climacteric fruits and can predict how quickly the fruit will ripen or decay. This physiological indicator is often used to monitor ripening progress and assess the product's response to postharvest treatments such as cooling or controlled-atmosphere storage (Kader, 2021).

In addition to intrinsic quality indicators, microbiological quality indicators are vital, especially from a food safety perspective. The presence and population of microorganisms such as bacteria, yeast, and mold can cause spoilage and even endanger consumer health. These indicators include the total microbial count and the presence of specific pathogens such as Salmonella or E. coli. Microbiological assessment is crucial for products consumed raw and is an integral part of quality assurance programs throughout the supply chain.

Sensory or organoleptic qualities, although subjective, are the most important quality indicators from a consumer perspective. These indicators include a product's color, aroma, taste, and texture. Color can be measured objectively with a colorimeter, but consumer perception of color is a strong visual indicator of quality. Aroma, derived from volatile compounds, can be measured chemically but also assessed by trained panelists. The integration of all these sensory attributes determines consumer preference and a product's marketability.

Correlations between various quality indicators often form the basis for shelf-life prediction models. For example, respiration rate and ethylene content data can be used to predict when fruit will reach peak ripeness. Similarly, firmness can be used as a proxy for starch content. By combining data from various indicators, postharvest practitioners can make more accurate decisions about when and how to market products.

Overall, understanding and applying quality indicators is the foundation of effective postharvest quality management. Without these objective measurement tools, it is impossible to evaluate the impact of postharvest treatments, minimize losses, and meet consumer expectations. Therefore, an OBE-based curriculum in postharvest physiology and technology should emphasize not only a theoretical understanding of these indicators but also students' practical skills in measuring, analyzing, and interpreting quality data to make strategic decisions (Thompson & Sargent, 2020).

CHAPTER 5
POST-HARVEST STORAGE TECHNOLOGY

Crop loss due to quality degradation is a major challenge in the global food system. To address this issue, postharvest storage technologies play a crucial role in maintaining quality, extending shelf life, and ensuring the availability of fresh produce for consumers. This approach focuses on controlling the metabolic rate of produce, which can be achieved through various methods. This chapter will explore in-depth the principles and applications of low-temperature storage methods, including refrigeration and freezing, as well as controlled atmosphere (CA) and modified atmosphere (MA) technologies that precisely control the gas composition surrounding produce. Furthermore, the chapter will discuss the concept of an integrated cold chain system and the development of energy-efficient storage innovations relevant to current climate challenges. Finally, these concepts will be brought together in an OBE-based project, where students will design an effective cold chain scheme for the distribution of horticultural produce.

4.3 Low Temperature Storage (Refrigeration, Freezing)

Low-temperature storage is a crucial post-harvest technology that slows respiration, inhibits enzymatic activity, and suppresses the growth of microorganisms that cause deterioration in horticultural products. These methods include refrigeration and freezing, both of which play a significant role in extending the shelf life of agricultural commodities. Refrigeration systems store products at temperatures close to the physiological optimum to suppress respiration without causing physiological damage, while freezing systems lower the temperature below the freezing point of water in the tissues, nearly halting metabolic activity. Therefore, this technology serves not only as a means of extending shelf life but also as a strategy to maintain product quality and ensure it remains suitable for consumption for a longer period (Thompson & Mejía, 2021).

In the context of cold storage or refrigeration, several aspects must be considered, including temperature and relative humidity control. Temperatures that are too high will accelerate metabolic processes and damage, while temperatures that are too low can cause chilling injury in sensitive tropical produce. Optimal relative humidity is crucial to prevent excessive water loss and prevent product loss and wrinkling. Therefore, temperature and humidity control technology in storage is a critical factor in successfully maintaining the quality of horticultural products. Recent research has shown that controlled cooling systems can slow enzymatic damage in climacteric and non-climacteric fruits, thereby maintaining freshness for longer (Singh et al., 2020).

In addition to temperature and humidity, controlled atmosphere storage and modified atmosphere packaging technologies are often combined with cold storage. Modified atmospheres, with reduced oxygen and increased carbon dioxide levels, have been shown to be effective in slowing respiration and inhibiting the growth of spoilage microorganisms. This combination of technologies provides more optimal results than conventional refrigeration alone. In practice, controlled atmosphere storage is widely applied to apples, pears, and grapes, while modified atmosphere packaging is used for small-sized fresh horticultural products. The integration of refrigeration with modified atmosphere packaging has been shown to extend product shelf life by up to two times compared to conventional storage (Kader & Yahia, 2020).

Freezing storage operates on a different principle than refrigeration, where the temperature is lowered to the freezing point of water in the product's tissues, typically below -18°C. Cooling to this temperature stops almost all metabolic activity and microbial growth. The main advantage of this method is its ability to preserve products for very long periods, even months or years. However, a major challenge in frozen storage is the formation of ice crystals, which can damage cell structures, thus reducing the texture of the product after thawing. Therefore, modern freezing technology has developed a quick freezing method to produce small ice crystals to minimize tissue damage (Thompson & Mejía, 2021).

The quality of frozen products is significantly influenced by the freezing speed and method used. Slow freezing tends to produce large ice crystals that damage cell walls, while rapid freezing with cold air flow or contact with cryogenic fluids produces smaller crystals that are safer for tissue. Furthermore, technologies such as individual quick freezing (IQF) are widely used in horticultural products, meat, and fish to maintain texture and facilitate handling in individually frozen form. The IQF method allows consumers to take portions of the product as needed without having to thaw the entire stored product, resulting in more efficient and hygienic food distribution (Singh et al., 2020).

Packaging plays a crucial role in the success of low-temperature storage in both refrigeration and freezing systems. Packaging materials must be able to protect the product from temperature fluctuations, water loss, and microbial contamination. In cold storage, packaging that can maintain relative humidity is essential to prevent weight loss, while in frozen storage, packaging must be airtight to prevent freezer burn. The selection of materials such as multilayer plastic, coated films, and vacuum packaging is key to maintaining product quality during storage. Recent innovations also include the use of active packaging that can absorb ethylene or inhibit microbial growth to extend shelf life (Kader & Yahia, 2020).

Energy efficiency in low-temperature storage is also a critical issue to consider. Modern refrigeration systems are not only required to maintain product quality but also to be energy-efficient and environmentally friendly. The use of environmentally friendly refrigerant technology with low global warming potential is a priority in today's storage designs. Furthermore, the implementation of sensor-based monitoring systems to monitor temperature and humidity in real time allows for more precise control of storage conditions, thereby reducing the risk of spoilage. Improving energy efficiency in the post-harvest supply chain significantly contributes to the sustainability of the food industry (Thompson & Mejía, 2021).

From a supply chain perspective, low-temperature storage technology directly contributes to global food availability. Without proper refrigeration, post-harvest losses can reach 30 to 40 percent of horticultural produce in developing countries. Cold and frozen storage enables the distribution of produce to international markets while maintaining quality, thereby increasing the added value of agricultural commodities. Thus, low-temperature storage is not only a post-harvest technology that maintains quality but also supports food security and sustainable global trade. This demonstrates that the integration of refrigeration technology into food logistics systems is a crucial part of building a resilient food system (Singh et al., 2020).

5.2 Controlled Atmosphere (CA)

Controlled atmosphere (CA) is a post-harvest storage technology based on regulating the gas composition within the storage space to slow the physiological processes of horticultural products. The main principle of this technology is to reduce oxygen levels and increase carbon dioxide levels to a specific concentration appropriate to the physiological needs of the commodity. This regulation suppresses the respiration rate, resulting in slower ripening and aging compared to conventional storage. CA technology is commonly used for high-value fruits such as apples, pears, and kiwifruit because it has been proven to extend shelf life while maintaining the sensory qualities desired by consumers (Thompson & Mejía, 2021).

Controlled atmosphere application must consider the physiological characteristics of the product because each type of fruit or vegetable has a different tolerance to low oxygen and high carbon dioxide levels. If the gas composition is not adjusted properly, physiological damage such as anaerobic fermentation can occur, which can lead to off-flavors or tissue damage. For example, apples can be stored in an atmosphere with around 1–2 percent oxygen and 1–3 percent carbon dioxide, while tropical bananas are more sensitive to low oxygen levels and require different settings. Therefore, intensive research on the atmospheric tolerance threshold for each commodity is crucial to determine effective operational standards for CA storage (Prasanna et al., 2020).

In addition to gas level control, temperature and relative humidity remain crucial components in CA storage. Low temperatures work synergistically with atmospheric controls to suppress respiration, while high humidity prevents excessive water loss. The combination of refrigeration and a controlled atmosphere results in stable storage conditions, thereby maintaining the texture, color, and nutritional content of horticultural products for longer. This technology has been shown to suppress the formation of compounds that cause enzymatic browning and slow the degradation of vitamin C in fresh fruit, thus maintaining nutritional value throughout storage (Singh et al., 2020).

The latest innovation in CA storage is the use of dynamic controlled atmosphere (DCA), which adjusts gas composition in real time based on the product's physiological response. This system uses non-destructive sensors to monitor respiration indicators or chlorophyll fluorescence, allowing oxygen levels to be lowered to the lowest safe limits. DCA technology allows for a longer shelf life of horticultural products compared to conventional CA without the risk of physiological damage. These advantages make DCA a potential alternative for expanding the global distribution of horticultural products while maintaining quality (Thompson & Mejía, 2021).

In the context of tropical commodities, the application of CA remains challenging because tropical products have high physiological diversity and tend to be sensitive to low oxygen levels. While some tropical fruits, such as mango, papaya, and guava, respond positively to CA, others are susceptible to damage when stored in atmospheres with too little oxygen. Therefore, research on adapting CA technology for tropical products continues to develop, particularly to support tropical fruit exports to international markets. With appropriate atmospheric conditions, shelf life can be extended up to twofold compared to storage with refrigeration alone (Prasanna et al., 2020).

The role of carbon dioxide in suppressing microbial growth cannot be ignored. Low-oxygen and high-carbon dioxide atmospheres have been shown to slow the growth of rot-causing fungi such as Botrytis cinerea in grapes and strawberries. This provides the added benefit of not only suppressing respiration rates but also reducing the need for chemical fungicides during storage. Thus, carbon dioxide not only supports shelf-life extension but also contributes to food safety and sustainable horticultural production (Singh et al., 2020).

Technically, CA implementation requires relatively high infrastructure investment, requiring airtight storage, gas control systems, and precise monitoring equipment. However, the economic benefits derived from reduced post-harvest losses and increased product value on the global market more than offset these investment costs. CA has been widely implemented in developed countries for high-value horticultural commodities, while its use in developing countries remains limited due to cost and infrastructure constraints. Therefore, collaboration between the private sector, government, and research institutions is needed to expand the application of this technology in tropical fruit-producing countries (Thompson & Mejía, 2021).

Overall, controlled atmosphere storage is a highly effective technology for extending shelf life, maintaining quality, and supporting international trade in horticultural products. By precisely regulating gas levels, this technology can slow aging, maintain sensory quality, and reduce post-harvest losses. Combining it with refrigeration and innovations such as dynamic controlled atmosphere storage makes this technology increasingly relevant in addressing global supply chain challenges. Therefore, a thorough understanding of product physiology and the development of CA storage technology needs to be taught in post-harvest physiology and technology courses to produce competent human resources in this field (Prasanna et al., 2020).

5.3 Modified Atmosphere (MA)

Modified atmosphere (AM) technology is a post-harvest storage method that involves changing the gas composition surrounding the product to slow the rate of respiration and other degradation processes. This method utilizes the physiological principle that the respiration rate of living commodities, such as fruits and vegetables, can be suppressed by lowering the oxygen (O2) concentration.) and increase the concentration of carbon dioxide (CO). Naturally, post-harvest commodities continuously consume Oand release COthrough the process of respiration. By controlling this gas exchange within a sealed package, the atmosphere surrounding the product is naturally modified. The goal is to create a suboptimal gas environment for microbial and enzyme metabolic activity, thereby extending the product's shelf life without the need for chemical preservatives. The application of MA becomes particularly relevant in the context of global supply chains, where products must remain fresh during long-distance transportation and distribution (Moser, 2017).

The working principle of MA is based on the selection of packaging materials that have selective permeability to certain gases, especially Oand CO. The polymer film used is designed in such a way that the rate of gas exchange (transmission) is balanced with the rate of respiration of the products within it. For example, Oconsumed by the product will be balanced with Owhich comes in from outside the packaging, while COThe resulting product will be balanced with COthat comes out. This balance creates a stable atmosphere with a concentration of Olow and COhigh. It is important to remember that each commodity has unique gas tolerances and requirements. If the concentration of Otoo low or COtoo high, the product can undergo anaerobic respiration which produces ethanol and acetaldehyde, causing unpleasant aromas and tastes (Siddiq & Nasir, 2017).

One of the most common applications of MA technology is in individual product packaging, known as MA packaging. This packaging is specifically designed to create and maintain optimal atmospheric conditions within the package. For example, broccoli packaging often uses a film with high O_2 permeability.to avoid anaerobic conditions, while strawberry packaging may require a different balance to control mold and spoilage. The success of MA packaging depends heavily on the physiological characteristics of the product, its respiration rate, storage temperature, and the permeability characteristics of the packaging material. Inappropriate packaging selection can lead to faster product quality degradation than no packaging at all.

Beyond individual packaging, the modified atmosphere concept is also applied on a larger scale, such as in bulk storage. However, this approach is more commonly referred to as controlled atmosphere (CA) storage, which involves more precise and active control of the gas composition within the storage space, rather than relying solely on the product's respiration. However, the basic principles of MA and CA are similar in terms of gaseous atmospheric manipulation. Both aim to suppress respiration rates, slow ripening, and reduce the production of ethylene, a hormone that accelerates fruit aging. By integrating MA with low-temperature storage (refrigeration), a synergistic effect can be achieved, significantly extending the shelf life of products several times over compared to low-temperature storage alone.

MA technology also plays an important role in suppressing the growth of microorganisms. Many spoilage microbes, such as fungi and bacteria, require Oto reproduce. By reducing the concentration of Oand increase CO, the growth rate of these microorganisms can be inhibited effectively. The concentration of COHigh concentrations of MA, in particular, have fungistatic and bacteriostatic effects, which help reduce spoilage. However, it is important to note that MA is not a sterilizer and cannot repair already contaminated produce. Therefore, the application of MA must be preceded by good sanitation and hygiene practices during post-harvest handling to ensure its effectiveness.

Although MA is highly effective, its implementation faces several challenges. One is the variability in respiration rates between products, even within a single variety, which can be affected by ripeness, harvest conditions, and handling. This makes it difficult to design a single type of MA packaging that is optimal for all conditions. Furthermore, mechanical damage to the packaging (e.g., a small puncture) can disrupt the atmospheric balance, causing the product to spoil more quickly. Therefore, quality control and packaging integrity throughout the supply chain are crucial.

Recent developments in MA technology include the use of smart packaging that can monitor atmospheric conditions in real time or packaging materials that can release antimicrobial or antioxidant compounds. These innovations aim to improve the effectiveness of MA and overcome its limitations. Furthermore, research is ongoing to identify optimal gas combinations for specific commodities, including combinations with other gases such as nitrogen and argon, to achieve synergistic effects. This demonstrates that MA is not a static technology, but a constantly evolving and adapting field.

Overall, modified atmosphere (MA) technology represents a smart and sustainable approach to extending the shelf life of agricultural products by leveraging the principles of postharvest physiology. By managing the gas composition surrounding the product, MA effectively suppresses respiration rates and microbial growth, contributing to reduced postharvest losses and improved product quality reaching consumers. The integration of MA with other storage technologies, such as refrigeration, will continue to play a central role in ensuring sustainability and efficiency in the global food system (Gómez-Limia et al., 2021).

5.4 Cold Chain System Technology

A cold chain system is an integrated network of processes, equipment, and procedures designed to maintain constant, low-temperature conditions for temperature-sensitive products, from the point of production to the consumer. This system is not limited to a single technology, but rather an orchestration of various components, including refrigeration facilities, insulated vehicles, specialized packaging, and careful logistics management. The goal is to minimize temperature fluctuations that can damage product quality, safety, and shelf life. Failure in any one link can compromise the entire system, resulting in significant product loss. Therefore, the cold chain is seen as a complex and vital ecosystem in the modern food, pharmaceutical, and biotechnology industries (Singh & Reddy, 2014).

The primary components of a cold chain system include cold storage facilities such as cold rooms and frozen warehouses, which serve as logistics hubs. These facilities are designed to hold large quantities of products at predetermined temperatures, often with automated temperature monitoring systems. Insulated transportation, such as refrigerated trucks, refrigerated containers, and refrigerated aircraft cargo, plays a crucial role in moving products from one point to another without exceeding critical temperature limits. These technologies must be equipped with precise temperature control systems to accommodate a wide range of product needs, from tropical fruits that require temperatures above 10°C to frozen products that must be kept below -18°C.

Packaging is also a crucial element in the cold chain system. Thermal packaging, such as insulated coolers with ice packs or gel packs, is used to protect products during the final stages of distribution, such as direct-to-consumer delivery or retail.

Innovations in smart packaging are also gaining adoption, with packages equipped with temperature indicators that change color or record temperature history during transit. This allows stakeholders to verify the integrity of the cold chain and identify when and where potential failures occur. Effective packaging helps maintain product temperature despite momentary external temperature fluctuations during handling.

Logistics management and monitoring are central to successful cold chain operations. This involves efficient route planning, delivery scheduling, and the use of information technology to track products in real time. Wireless temperature sensors and data loggers are installed on products or in vehicles to continuously monitor temperatures. This data is then analyzed to ensure compliance with established temperature standards and to detect anomalies that may indicate problems. This comprehensive data allows for immediate corrective action and provides transparency to all parties along the chain.

The implementation of a cold chain system is essential for highly perishable products. In horticultural products, this system effectively slows respiration rates, ethylene production, and the development of spoilage microorganisms. This directly contributes to a significant reduction in post-harvest losses, which often reach 30-50% in developing countries due to poor handling and a lack of adequate storage facilities. With a cold chain, agricultural products from rural areas can reach urban and even international markets with maintained quality.

However, implementing a cold chain system is not without challenges. High initial investment costs for refrigeration facilities and equipment, as well as high operational costs, particularly electricity, are often significant barriers, particularly in developing countries. Inadequate infrastructure, such as unstable access to electricity, can also hinder the system's effectiveness. Furthermore, inadequate awareness and training among actors along the supply chain can lead to handling errors that compromise the system's integrity, such as leaving the refrigerator door open for too long or not promptly transferring products to the refrigerator upon arrival.

The future of cold chain technology is geared toward greater efficiency and sustainability. The development of more energy-efficient cooling technologies, the use of renewable energy, and the design of better insulation materials are key focuses. Innovations in passive and thermoelectric cooling systems are also being explored to reduce reliance on conventional mechanical refrigeration. Furthermore, the integration of digital technologies, such as the Internet of Things (IoT) and blockchain, offers the potential to improve product visibility and traceability along the chain, ultimately enhancing security and consumer trust (Hussain & Al-Alawi, 2016).

Overall, the cold chain system is more than just technology, it is a vital strategic framework for ensuring food safety and the sustainability of global supply. By maintaining optimal temperature conditions from farmer to consumer, this system not only reduces post-harvest losses and increases product shelf life, but also opens up new market opportunities and improves logistics efficiency. Its crucial role in ensuring product quality, particularly in the food and pharmaceutical sectors, makes it a key pillar of modern post-harvest technology (Gómez-Limia et al., 2021).

5.5 Energy-Friendly Storage Innovations

Energy-efficient storage innovation in post-harvest storage has become a key focus as the need to reduce operational costs and the environmental impact of conventional refrigeration systems increases. Storing horticultural products generally uses significant amounts of electricity, particularly in industrial-scale facilities. Therefore, developing energy-efficient technologies that maintain product quality presents both a challenge and an opportunity to improve the efficiency of the food supply chain. Widely studied approaches include the use of environmentally friendly refrigerants, renewable energy-based refrigeration systems, and high-performance insulation technologies that can reduce energy loss during storage (James & James, 2021).

The use of renewable energy, particularly solar energy, has become a key innovation in energy-efficient storage. Solar-powered cold storage systems are widely used in tropical and rural areas with limited access to conventional electricity. This technology utilizes photovoltaic panels to generate energy for the cooling system, reducing reliance on fossil fuels. Furthermore, battery storage technology continues to be developed to ensure stable power supplies during nighttime or cloudy weather, making solar-powered cold storage increasingly commercially viable (Kitinoja & Thompson, 2020).

In addition to utilizing renewable energy, developing thermal insulation technology is also key to energy-friendly storage innovation. Insulation materials with low thermal conductivity can reduce energy loss from storage spaces, thereby reducing the power requirements for maintaining stable temperatures. Material innovations such as vacuum insulated panels (VIPs) and phase change materials (PCMs) are widely researched for applications in cold storage. PCMs, in particular, have the ability to absorb and release latent energy at specific temperatures, thus maintaining stable storage temperatures with lower energy consumption than conventional refrigeration (Prasanna et al., 2020).

The concept of smart cold storage is also becoming an increasingly relevant innovation with the development of digital technology. Smart storage systems use Internet of Things (IoT)-based sensors to monitor temperature, humidity, and atmospheric conditions in real time. The data obtained can be analyzed to optimize energy use by automatically adjusting cooling according to product needs. This ensures energy is not wasted on overcooling, while maintaining product quality. This digital technology integration also supports transparency in the supply chain, facilitating the tracking and quality control of horticultural products (James & James, 2021).

From a refrigerant perspective, a key innovation in energy-friendly storage is the use of natural refrigerants such as carbon dioxide, ammonia, and hydrocarbons, which have low global warming potential. Conventional refrigerants, such as hydrofluorocarbons (HFCs), have been shown to significantly impact climate change, leading to restrictions on their use in many countries. The development of natural refrigerant-based cooling systems not only reduces environmental impact but is also more energy efficient. This aligns with the global trend toward sustainable storage, which focuses not only on economic efficiency but also on ecological sustainability (Kitinoja & Thompson, 2020).

The use of hybrid energy is also gaining popularity as an innovative solution for energy-efficient storage. Hybrid systems combine renewable energy sources with conventional electricity grids, providing greater flexibility in ensuring operational continuity. For example, refrigeration can rely on solar energy during the day and switch to conventional electricity at night. This approach not only reduces energy costs but also improves system reliability, especially in areas with unstable electricity supplies. The implementation of hybrid cold storage is an effective strategy for expanding fresh food distribution in remote areas (Prasanna et al., 2020).

Furthermore, the concept of decentralized storage is also part of energy-friendly innovation. By building small-scale cold storage close to production sites, the distribution chain can be shortened, reducing energy requirements for transportation and long-term cooling. This decentralized model is particularly beneficial for smallholder farmers in tropical regions, who often face high post-harvest losses due to limited storage facilities. Through local, renewable energy-based storage, products can be marketed at higher quality, thereby increasing their economic value (James & James, 2021).

Overall, energy-friendly storage innovations not only offer technical solutions to reduce energy consumption but also positively impact food security and environmental sustainability. The combination of technologies such as renewable energy, advanced thermal insulation, intelligent digital systems, and the use of natural refrigerants points to a greener future for postharvest storage. Therefore, it is crucial to introduce these innovations in OBE-based postharvest physiology and technology studies so that students not only understand storage principles but also integrate sustainability aspects into food industry practices (Kitinoja & Thompson, 2020).

5.6 OBE Project: Design a Cold Chain Scheme for Distribution of Leafy Vegetables from Farms to Modern Markets

This Outcome-Based Education (OBE) project aims to design an efficient and sustainable cold chain scheme for the distribution of leafy vegetables, such as spinach and lettuce, from the farm level to modern markets. The project will emphasize the importance of integrating post-harvest physiology knowledge with modern storage technologies. The output of this project will be a prototype of a workable cold chain scheme, complete with technicall, economic, and sustainability analyses. Students will work in teams, collect data directly in the field and conduct literature reviews to develop solutions relevant to local conditions.

OBE Project Implementation Stages

A. Problem Identification and Analysis

The initial stage involves a thorough understanding of the current conditions. Students will conduct surveys in leafy vegetable farmers' gardens and in modern markets. Observations will focus on: (1) Existing harvesting and post-harvest handling methods, (2) Temperature and humidity at each point in the supply chain (harvesting, transportation, temporary storage), and (3) Post-harvest damage and loss levels (e.g., wilting, yellowing, rotting). These data will form the basis for formulating key issues that need to be addressed, such as high respiration and transpiration rates that cause products to wilt quickly.

B. Cold Chain Scheme Design

Based on the data collected, the student team will design a comprehensive cold chain scheme. This design should include:

1. Pre-cooling Technology: Propose pre-cooling methods in the orchard, such as hydro-cooling or forced-air cooling, to immediately lower the temperature of the product after harvest.
2. Packaging System: Design appropriate packaging, such as insulated packaging or packaging with effective ice packs, to maintain low temperatures during transport.

3. Logistics and Transportation: Determine the type of vehicle (e.g., insulated box or refrigerated truck) and efficient distribution route from the farm to the distribution center and market.
4. Storage in the Market: Propose the specifications of cooling units in the modern market that can maintain the optimal temperature of leafy vegetables (around 0-4°C) and high relative humidity (95-100%).
5. Monitoring System: Design a simple temperature monitoring system using data loggers or thermal sensors to ensure cold chain integrity is maintained.

C. Implementation Projection and Feasibility Analysis

Once the schematic is designed, the team will create implementation projections. The feasibility analysis will include:

1. Technical Analysis: Assess the suitability of the proposed technology with the availability of infrastructure and farmer labor.
2. Economic Analysis: Calculate the initial investment costs (e.g., pre-cooling equipment, packaging, and transportation costs) as well as potential savings from reduced post-harvest losses and increased selling prices of high-quality products.
3. Sustainability Analysis: Evaluate the environmental impact of the proposed scheme, including energy consumption and the use of recyclable packaging materials. Students may propose the use of renewable energy (e.g., solar-powered cooling) where relevant.
4. Outcome Assessment: Develop metrics to measure project success, such as percentage reduction in post-harvest losses, increased shelf life, and market response to fresher products.

Learning Outcomes

This project is expected to produce outcomes that are in accordance with the OBE framework, including:

1. Cognitive:Students understand the principles of post-harvest physiology of leafy vegetables and can integrate them with cold chain technology.
2. Psychomotor:Students are able to design relevant and practical technical schemes for real problems in the field.
3. Affective:Students develop teamwork, communication, and critical thinking skills to solve problems holistically and responsibly.

The project will conclude with a presentation of a prototype cold chain scheme to relevant stakeholders, such as farmer representatives, modern market management, and academics. This not only tests students' understanding and skills but also provides a tangible contribution that could provide solutions to post-harvest challenges in Indonesia.

CHAPTER 6
Post-Harvest Packaging Technology

Postharvest Packaging Technology is a crucial element in the agricultural supply chain, complementing the storage system. It provides an in-depth discussion of the function and role of packaging, which extends beyond its mere function as a container, to a physical barrier, a barrier to gas and water vapor transfer, and a medium for product information. The chapter then outlines various types of packaging, from long-established conventional packaging to active packaging designed to interact with the product inside, and eco-friendly packaging focused on sustainability. Specifically, edible coatings and biopolymers will be explored as innovations that reduce waste and naturally extend shelf life. Recent developments will also be discussed, such as smart packaging innovations that provide real-time information on product conditions, such as temperature and freshness. All of these theoretical concepts will be integrated into the OBE Project, where students will directly practice creating a chitosan-based edible coating for mangoes.

6.1 Function and Role of Packaging

Post-harvest packaging serves a role far beyond its physical container. Fundamentally, packaging serves as the primary protection for produce from various external factors that can cause damage, whether mechanical, biological, or environmental. Mechanical damage, such as impact or pressure, often occurs during handling and transportation, which can cause bruising, cuts, or breaks in produce. Properly designed packaging, such as that made of rigid or cushioned materials, can absorb and distribute these forces, maintaining the product's physical integrity. Furthermore, packaging protects produce from microbial contamination, dust, and insects, which can accelerate spoilage and reduce product quality. Without this protection, perishable agricultural produce will experience significant losses and losses, reducing the efficiency of the entire supply chain.

One of the critical functions of packaging is its role in controlling the microenvironment surrounding the product. Modern packaging is designed to control gas exchange, humidity, and light. Respiration and transpiration, as natural physiological processes of post-harvest produce, continuously release water vapor, carbon dioxide (CO_2), and ethylene. Appropriate packaging can modify the atmosphere within, for example by decreasing the oxygen (O_2) concentration and increasing CO_2, effectively slowing the rate of respiration and product aging. Humidity control is also crucial, as water vapor loss can lead to wilting and weight loss, which directly impact quality and market value. Thus, packaging acts as a selective barrier that creates optimal conditions for extending the shelf life of products.

The role of packaging is not limited to protecting and modifying the internal environment, but also serves as an information and marketing medium. Each package carries a label that communicates important information to consumers, such as the product name, net weight, expiration date, storage instructions, and nutritional information. This information is crucial to ensuring consumers use the product correctly and safely. Furthermore, packaging is also a powerful marketing tool. Attractive designs, colors, and logos can influence consumer purchasing decisions at the point of sale. In modern contexts, packaging is also often used to communicate brand values, such as sustainability or product origin, which can build consumer loyalty (Robertson, 2013).

From a logistics perspective, packaging plays a crucial role in efficient handling, transportation, and storage. Standardized packaging, such as boxes or crates, facilitates unitization, where products are grouped into larger units for bulk handling. This allows for the use of pallets, forklifts, and warehouse automation systems, which speed up logistics processes and reduce labor costs. Strong, stackable packaging also saves storage and transportation space, allowing more products to be transported in a single trip. Without effective packaging, handling fragile agricultural products would be extremely difficult and prone to damage.

Beyond traditional functions, packaging is now evolving by adding more sophisticated features. Active packaging is one innovation designed to intentionally interact with the product or its environment. Examples include oxygen scavengers that absorb residual O2, ethylene absorbers that inhibit ripening, and antimicrobial compounds that suppress bacterial or fungal growth. This type of packaging offers more proactive protection, going beyond the passive role of conventional packaging, and is becoming increasingly important for highly sensitive and perishable products (Siddiq & Nasir, 2017).

The role of packaging also extends to sustainability. Eco-friendly packaging, such as that made from recycled, biodegradable, or renewable materials, is becoming a major focus in the industry. Consumers are increasingly aware of the environmental impact of single-use plastic packaging, prompting manufacturers to seek greener alternatives. However, developing eco-friendly packaging often faces challenges in maintaining both its protective and functional properties. Therefore, research is ongoing to find materials that balance performance and environmental impact (Kumar & Kumar, 2020).

Economically, packaging contributes significantly to a product's added value. Well-packaged products not only have a longer shelf life but also have greater visual appeal, allowing producers to command premium prices. Reducing post-harvest losses, which can reach 30% without proper packaging, directly increases profitability. Therefore, investing in post-harvest packaging technology can be considered a significant savings investment across the entire value chain.

Thus, post-harvest packaging is not merely an accessory, but rather an essential strategic element in maintaining product quality, safety, and value. Its diverse functions, ranging from physical protection and environmental modification to informative and marketing roles, emphasize that packaging is an integral part of post-harvest technology. A thorough understanding of these functions and roles is crucial for everyone involved in the food industry, as effective packaging is key to delivering fresh and safe products to end consumers.

6.2 Types of Packaging (Conventional, Active, Environmentally Friendly)

Conventional packaging has been a key pillar of the post-harvest industry for decades. This type of packaging, often made from synthetic polymers such as polyethylene (PE), polypropylene (PP), or polyvinyl chloride (PVC), serves as a passive physical barrier. Its primary role is to protect the product from mechanical damage, microbial contamination, and changes in the external environment. Conventional packaging is effective in preventing product wilting by limiting transpiration, and also protects against dust and dirt. However, its passive nature has limitations, it does not actively interact with the product, and therefore cannot suppress respiration or the growth of existing microorganisms. Nevertheless, conventional packaging remains an economical and reliable option for many commodities with relatively short shelf lives.

As understanding of post-harvest physiology has grown, active packaging has emerged as an evolution of conventional packaging.

Active packaging is designed to intentionally interact with the product or its surrounding environment to extend shelf life and improve quality. This interaction occurs through the release or absorption of specific substances. The most common examples are oxygen scavengers placed inside the package to reduce O2 concentration and prevent oxidation, or ethylene scavengers that absorb ethylene gas, a ripening hormone that accelerates aging in climacteric fruits. This innovation is particularly useful for products sensitive to oxygen or ethylene, such as berries, cut vegetables, and meat products. The effectiveness of active packaging relies heavily on the intentional interaction between the packaging material, additives, and the product itself, making it a more proactive and intelligent solution.

In addition to gas absorbers, active packaging also includes antimicrobial or antioxidant release systems. The release of antimicrobial compounds, such as silver nanocomposites or natural ingredients, can inhibit the growth of bacteria and fungi on the surface of the product, thereby reducing the risk of spoilage and foodborne illness. Meanwhile, the release of antioxidants helps prevent oxidative reactions that can cause color and flavor changes. According to Robertson (2013), the integration of these substances into the packaging polymer matrix allows for controlled and sustained release, providing more effective protection throughout the product's life cycle. While they have a higher cost than conventional packaging, the benefits in reducing food loss and improving food safety are often comparable.

On the other hand, growing global awareness of environmental issues has driven the development of eco-friendly packaging. This type of packaging encompasses a variety of materials that are recyclable, biodegradable, or derived from renewable sources (bio-based). Biodegradable packaging, for example, is made from natural polymers such as starch, cellulose, or polylactide (PLA), which decompose into organic matter in suitable environments. Its primary advantage is reducing the accumulation of non-biodegradable plastic waste. However, the main challenge for eco-friendly packaging often lies in its barrier performance, which is sometimes lower than that of conventional plastics, and its relatively high production costs.

One important innovation in the eco-friendly packaging category is edible coatings made from biopolymers. These thin layers are applied directly to the surface of the product and act as a semi-permeable barrier to control gas and water vapor exchange. These coatings are generally made from proteins (such as collagen or casein), polysaccharides (such as starch or carrageenan), or lipids. Their primary function is to slow transpiration, reduce respiration rates, and can even be enriched with natural antimicrobials or antioxidants to provide additional protection (Kumar & Kumar, 2020). Edible coatings are ideal for fruits and vegetables sold whole, as they eliminate the need for external plastic packaging, thus minimizing waste.

The latest development in packaging technology is smart packaging. Unlike active packaging, which interacts with the product, smart packaging functions as a sensor or indicator that provides information about the product's condition in real time. Examples include time-temperature indicators that change color as temperature exposure accumulates, leak sensors that detect damage to the packaging, or freshness indicators that measure volatile gases released by the product as it decomposes. Smart packaging is invaluable to consumers and supply chain managers because it provides full visibility into the product's history. This aids in decision-making about when the product should be sold or consumed, thereby reducing food waste.

Smart packaging systems often utilize chemical sensor technology and printed electronics. Chemical sensors can detect changes in the concentration of gases such as ethylene, ammonia, or CO2, which are important markers of ripeness or spoilage. This information can then be visualized through color changes on labels or read by electronic devices. According to Hussain and Al-Alawi (2016), smart packaging is revolutionizing cold chain management by providing unprecedented data, enabling logistics optimization and better quality assurance from producer to consumer.

Overall, the evolution of postharvest packaging technology demonstrates a shift from passive solutions to more dynamic and integrated systems. From simple, conventional packaging, to active packaging that interacts functionally, to eco-friendly packaging that prioritizes sustainability, and culminating in smart packaging that provides critical information. Each type of packaging has a specific and relevant role, depending on product characteristics, market objectives, and economic and environmental considerations. A comprehensive understanding of these packaging types is crucial for selecting the most effective packaging strategy to enhance the shelf life and quality of postharvest products.

6.3 Edible Coatings and Biopolymers

Edible coatings and biopolymers are crucial innovations in post-harvest packaging technology, particularly in addressing the challenges of plastic waste and naturally extending the shelf life of agricultural products. Edible coatings are thin layers applied directly to the surface of food products and can be consumed simultaneously with them. These layers act as a functional barrier that controls the exchange of gases and water vapor between the product and the external environment. By suppressing respiration and transpiration rates, edible coatings effectively slow the aging process, maintain firmness, and reduce wilting. Unlike conventional packaging, which must be removed, edible coatings contribute to reducing packaging waste, in line with sustainability principles.

The basic ingredients of edible coatings are biopolymers, polymers derived from biological sources. These biopolymers can be categorized into three main groups: proteins, polysaccharides, and lipids. Protein polymers, such as collagen, casein, or soy protein, have good film-forming properties and can provide mechanical strength. Polysaccharides, such as starch, cellulose, alginate, and pectin, are very effective at forming a barrier layer against gases such as oxygen. Meanwhile, lipids, such as beeswax, fatty acids, or oils, excel as water vapor barriers. Using a single biopolymer often does not provide all the necessary barrier properties, so effective edible coating formulations often combine several types of biopolymers to create a layer with balanced functional properties.

In addition to acting as a physical barrier, edible coatings can also function as carriers for active ingredients. Natural antimicrobials and antioxidants can be integrated into coating formulations to provide additional protection against microbial and oxidative degradation. Examples of commonly used antimicrobials include essential oils (such as oregano or thyme oil), plant extracts, and antimicrobial peptides. The addition of antioxidants, such as vitamins C or E, helps prevent enzymatic browning and maintains product color. This integration allows edible coatings to proactively extend product shelf life in a safe and natural manner, reducing the need for synthetic preservatives (Kumar & Kumar, 2020).

Edible coating application varies depending on the product type and coating formulation. The most common method is dipping, where the product is immersed in a coating solution for a short period of time. Other methods include spraying or brushing. The choice of application method should take into account product characteristics, such as sensitivity to water or surface texture. After application, the product is dried to form a thin, uniform layer. This drying process is crucial to ensure strong and effective film formation. Optimizing temperature and humidity during drying is key to avoiding cracks in the coating that could reduce its effectiveness.

Despite its significant potential, the application of edible coatings faces several challenges. One major challenge is ensuring the consistency and effectiveness of the coating on products with uneven surfaces, such as strawberries or broccoli. Variability in ingredient formulation, application methods, and environmental conditions can impact coating performance. Furthermore, some consumers may be unfamiliar with the concept of consuming a thin coating on fresh produce, requiring market education. Economically, the production and application costs of edible coatings can still be higher than those of conventional plastic packaging, although the benefits in waste reduction and shelf life extension may offset these costs in the long run.

One of the biopolymers widely studied for edible coatings is chitosan. Chitosan, extracted from the shells of shrimp, crabs, and other crustaceans, has remarkable antimicrobial properties and the ability to form strong films. Its antimicrobial properties stem from the positive charge of chitosan molecules, which can interact with negatively charged microbial cell membranes, causing leakage and cell death. Research shows that chitosan-based edible coatings are effective in inhibiting mold growth on fruits such as strawberries and mangoes (Siddiq & Nasir, 2017). Chitosan is also a renewable and biodegradable material, making it a highly environmentally friendly choice.

The development of edible coatings and biopolymers also opens up new opportunities for added value to agricultural products. Agricultural biomass waste, such as fruit peels, pulp, or crop residues, can be extracted to produce biopolymers, which are then reused as raw materials for coatings. This creates an efficient circular economy, where waste from one process becomes raw material for another. Utilizing agricultural waste not only reduces production costs but also provides a sustainable solution for agro-industrial waste management.

In conclusion, edible coatings and biopolymers represent a paradigm shift in postharvest packaging technology. They not only offer physical protection but also act as active barriers, carriers of functional substances, and environmentally friendly solutions. While implementation challenges remain, their potential to reduce postharvest losses, improve food quality and safety, and promote sustainability makes them a crucial area of research and development in food science.

6.4 Smart Packaging Innovation

Smart packaging represents a significant advancement in post-harvest technology, going beyond the basic physical protection and information provided by conventional packaging. The concept is defined as a packaging system that monitors the condition of the product inside or the surrounding environment and communicates this information to the consumer (Ammor & Böhme, 2021). The key difference lies in its ability to provide real-time data on product quality and safety. Smart packaging thus acts as the eyes and ears of a product, providing visual, electronic, or even wireless signals indicating freshness, temperature, or other relevant conditions. Its central role is to bridge the information gap between producers, distributors, and consumers, enabling more informed decision-making and minimizing food safety risks.

One of the most widely implemented types of smart packaging is the time-temperature indicator (TTI). This indicator is a small label attached to the packaging and undergoes visual changes, such as color or shape, that directly correlate with the product's temperature history (Kuswandi, 2020). TTI is particularly important for products sensitive to temperature fluctuations, such as frozen foods, seafood, and dairy products. Its mechanism is based on chemical, enzymatic, or polymerization reactions whose rates are temperature-dependent. Visual changes observed by consumers or supply chain members provide an early warning if the product is exposed to suboptimal temperature conditions, helping prevent risky consumption and reducing economic losses due to product spoilage.

In addition to TTI, gas sensors also play a crucial role in smart packaging, particularly for horticultural products. Fruits and vegetables produce ethylene gas as they ripen, and detecting this gas can be a powerful indicator of ripeness and potential spoilage. Gas sensors in smart packaging can detect volatile compounds released by spoilage microorganisms, such as ammonia or sulfur compounds. These systems work with responsive materials that change their properties when interacting with the target gas, for example by changing color or electrical resistance. Their application allows producers to optimize harvest and delivery times, while consumers can visually monitor product freshness without having to open the package.

The core components of smart packaging consist of three elements: sensors, electronic tags or indicators, and the packaging substrate itself. The sensors, which are the core of these systems, can be chemical sensors, biosensors, or physical sensors designed to detect specific variables such as temperature, humidity, pH, or gas concentration. Electronic tags such as RFID (Radio Frequency Identification) or NFC (Near Field Communication) serve as a wireless communication medium, allowing data collected by the sensors to be read remotely using a reader device. The integration of these components requires innovation in materials and manufacturing techniques to allow them to be printed or applied to flexible or rigid packaging cost-effectively and with high functionality.

The use of smart packaging offers numerous benefits, particularly in reducing food waste and increasing consumer confidence. By providing accurate information about shelf life and freshness, consumers are less likely to throw away products that are still edible (Gupta & Choudhury, 2022). Manufacturers can also optimize distribution and inventory, reducing losses from expired products. Product safety is also improved because smart packaging can detect microbial contamination or cold chain failures. These advantages collectively contribute to a more sustainable food system, where resources spent on production and distribution are not wasted because products are discarded before reaching consumers.

Despite its promise, smart packaging implementation faces several challenges. Relatively high production costs, particularly for sensor- and electronic chip-based technologies, pose a significant barrier to mass adoption. Furthermore, sustainability is a concern. Integrated electronic components are often difficult to recycle, which contradicts global goals to reduce waste. Technology standardization and regulations are also not yet fully developed, hindering interoperability and widespread adoption across global supply chains. Therefore, current research and development focuses on sensors that can be made from more environmentally friendly materials and more cost-effective manufacturing processes.

The future prospects for smart packaging are bright with the integration of more advanced technologies. One key direction is to combine smart packaging with the Internet of Things (IoT). Through IoT, data collected by packaging sensors can be uploaded to the cloud and accessed in real time by all stakeholders, from farmers to retailers. This enables more sophisticated logistics monitoring, predicting potential issues, and optimizing delivery routes. The development of new sensors that are more sensitive and specific to various types of product degradation, as well as sensors that can interact directly with consumers through smartphone apps, will also open up new opportunities for personalized information and interactions.

Overall, smart packaging is a game-changer in post-harvest physiology, transforming packaging from a static container into an active partner in maintaining product quality and safety. With its ability to monitor, identify, and communicate critical information, this technology contributes to waste reduction, increased supply chain efficiency, and strengthened consumer trust. While challenges remain, continued investment in research and development, particularly in sustainable materials and integration with digital systems, will drive wider adoption and enable a more efficient and responsible food supply chain in the future.

6.5 OBE Project: Making Chitosan-Based Edible Coating for Mangoes

Project Title: Making Chitosan-Based Edible Coating for Mangoes

A. Project Background

Mangoes are a tropical fruit commodity with high economic value, but they have a short shelf life due to high respiration and transpiration rates after harvest. This phenomenon causes significant losses for farmers, distributors, and consumers. Edible coating, or a protective layer that can be eaten, is an innovative solution in post-harvest technology to extend the shelf life of fruit. Chitosan, a natural polymer derived from shrimp or crab shell waste, has biodegradable, biocompatible, and antimicrobial properties that make it highly effective as a base material for edible coatings (Ammor & Böhme, 2021). This project is designed to provide students with practical experience in designing, implementing, and evaluating the effectiveness of a chitosan-based edible coating on mangoes, in line with the OBE-based learning approach.

B. Learning Objectives (Graduates)

This project aims to achieve several Learning Outcomes (LOs) relevant to the Postharvest Physiology and Technology course:

1. LO 1: Students are able to understand and explain the principles of fruit physiology after harvest, including respiration, transpiration, and ripening.
2. LO 2: Students are able to design and formulate optimal chitosan-based edible coating formulations.
3. LO 3: Students are able to apply edible coating to mangoes and evaluate its effectiveness in extending shelf life.
4. LO 4: Students are able to analyze data, present findings systematically, and communicate project results orally and in writing.

C. Project Activity Plan

This project will be implemented in several main stages:

1. Preparation Stage (Weeks 1-2)
   a) Literature Study: Students conducted a literature review on post-harvest physiology of mangoes and the formulation of chitosan-based edible coatings.
   b) Chitosan Solution Formulation: Students make chitosan solutions with different concentrations (for example, 0.5%, 1.0%, and 1.5%) and other additional materials (glycerol as a plasticizer).
   c) Procurement of Materials: Prepare mangoes with uniform ripeness and the required chemicals.
2. Implementation Phase (Weeks 3-6)
   a) Coating Application:Mango fruit was divided into four groups: one control group (without coating) and three treatment groups (with different concentrations of chitosan).
   b) Parameter Observation:Students routinely observe and measure physiological parameters and mango quality every 2-3 days. The parameters observed include:
      1) Weight Loss (%): Measuring water loss due to transpiration.
      2) Fruit Hardness: Using a penetrometer to measure the hardness of the fruit flesh.
      3) Total Dissolved Solids (TPT): Using a refractometer to measure sugar content, as an indicator of ripeness.
      4) Visual Display: Observe changes in skin color, presence/absence of spots, and signs of decay.
3. Analysis and Reporting Stage (Weeks 7-8)

a) Data analysis:Students process the collected data, comparing the effectiveness of each coating treatment against the control group.
b) Report Preparation:Write a project report that includes background, methodology, results, discussion, and conclusions.
c) Presentation of Results:Presenting project findings to lecturers and other students.

4. Assessment Method

Project assessment will be conducted holistically to measure the achievement of each Learning Outcome (LO).

a) Formative Assessment:
    1) Weekly report: Assessment of student progress and understanding during the implementation stage.
    2) Group Discussion: Assessment of participation and contribution of each team member.
b) Summative Assessment:
    1) Final Project Report: Assess students' ability to analyze data, present findings, and write academically (referring to LO 1, 2, 3, and 4).
    2) Project Presentation: Assess oral communication skills, conceptual understanding, and responses to questions (refer to LO 1 and 4).
    3) Practical Demonstration: Assessment of technical skills in formulating and applying coatings (referring to LO 2 and 3).

CHAPTER 7
Post-Harvest Preservation Technology

Post-harvest preservation methods can be grouped into several main categories to maintain the quality and extend the shelf life of agricultural products. Physical methods utilize physical principles such as cooling to slow metabolism, drying to reduce water content, and irradiation and mild heating to control microorganisms. Furthermore, chemical methods use ingredients such as natural preservatives and GRAS (Generally Recognized As Safe) compounds to inhibit pathogen growth. Meanwhile, biotechnology methods offer modern solutions through the application of enzymes, probiotics, and nano-bio coatings for more advanced protection. Fourth, a combination of technologies, known as Hurdle Technology, combines several of the above methods to create a synergistic effect, making preservation more effective and efficient.

6.1 Physical Methods: Cooling, Drying, Irradiation, Light Heating

Cooling is the most widely used physical method for preserving agricultural products because it suppresses respiration, transpiration, and enzymatic activity, which accelerate deterioration. Freshly harvested horticultural products often have high temperatures, making rapid cooling, or precooling, a critical step in maintaining quality. Various techniques, such as forced-air cooling, hydrocooling, vacuum cooling, and evaporative cooling, are used depending on the characteristics of the commodity. Cooling not only maintains visual freshness but also prevents the growth of pathogenic microbes that can compromise food safety. Therefore, the application of this technology must be adapted to the needs of modern distribution, which demands high hygienic standards (Ferdousi et al., 2024).

Vacuum cooling is an effective form of advanced cooling for leafy commodities such as lettuce, cabbage, and spinach. Its principle is based on the evaporation of the product's internal water under low pressure, resulting in a rapid and even cooling effect. This technique can reduce the temperature by up to 2°C in less than 30 minutes, significantly faster than conventional cooling. Another advantage is energy efficiency, although the risk of water loss must be addressed with appropriate packaging to prevent texture degradation. In the context of OBE, students need to understand the balance between technical efficiency and the physiological impact of the product to assess its potential application in the field.

Drying is another physical method widely used to reduce moisture content, slow microbial growth, and suppress chemical reactions that accelerate spoilage. In the last decade, drying methods have undergone significant developments, including the use of infrared drying and vacuum drying, which shorten processing times while maintaining nutritional quality. Infrared drying, for example, allows for more efficient heat penetration and better color and bioactive content preservation compared to conventional drying. The use of a combined infrared-vacuum method has even been shown to be more energy efficient and produces dried products with a texture and flavor preferred by consumers (Delfiya et al., 2021).

Recent innovations in drying also emphasize the preconditioning stage before the process takes place. Pretreatment using ingredients such as ascorbic acid, sodium metabisulfite, or physical treatments such as ultraviolet light and superheated steam have been shown to maintain antioxidant activity and improve product color. Furthermore, the combination of low-pressure superheated steam drying (LPSSD) with chemical preconditioning has been shown to reduce microbial counts below permissible thresholds. This method confirms that drying is not merely about reducing water content but also an integral strategy for ensuring food safety while maintaining sensory quality.

Irradiation is a physical method gaining acceptance in post-harvest technology because it does not involve significant temperature increases, hence the name cold pasteurization. The use of gamma rays, high-energy electron beams (e-beams), or ultraviolet light can reduce microbial populations, delay ripening, and extend shelf life. In horticultural commodities, low-dose irradiation has been shown to be effective in delaying physiological changes such as tissue softening or pigment degradation. However, a major challenge is consumer acceptance, as many still associate irradiation with radioactivity despite research demonstrating its safety.

Irradiation applications on edible fungi, such as edible mushrooms, have shown promising results. Treatment with doses of 1–3 kGy can delay cap opening, slow stem growth, and reduce microbial spoilage. These positive effects are further enhanced when combined with refrigeration or modified atmosphere packaging, as they provide a synergistic effect on shelf life extension. Furthermore, research shows that irradiation does not cause significant changes in the protein and polysaccharide content of mushrooms, thus still meeting expected nutritional standards (MDPI, 2022).

Although irradiation is effective in extending shelf life, the dosage used must be strictly controlled to avoid sensory quality degradation. Doses of 1–2 kGy generally maintain color, texture, and aroma, while higher doses can potentially cause changes in taste and decreased consumer acceptance. Therefore, the principle of caution in determining dosage is an important competency for students studying postharvest physiology and technology, particularly in applying this method to various commodities with different characteristics.

In addition to cooling, drying, and irradiation, mild heat treatment is also gaining attention as an alternative physical method. Brief heating at relatively low temperatures is used to inactivate enzymes that cause browning or softening without destroying heat-sensitive nutrients. This technology is commonly applied to fruit juices or minimally processed fresh products, with the goal of extending shelf life while maintaining natural sensory qualities. The combination of mild heating and cooling produces the dual effect of suppressing microbes and maintaining freshness.

Mild heating is often combined with other technologies such as modified atmosphere packaging, allowing for longer product quality. The advantage of this method lies in its ability to preserve vitamin C, phenolic compounds, and antioxidant activity better than conventional pasteurization. However, the success of this method depends heavily on temperature and time parameter control, as even slight errors can lead to sensory deterioration. Therefore, in the context of OBE learning, students need to learn laboratory practices that emphasize precision in application.

The application of physical methods in post-harvest technology is not only related to shelf-life extension but also has relevance to the sustainability of food systems. Efficient cooling can reduce post-harvest food losses, energy-efficient drying supports emission reductions, irradiation reduces the need for synthetic chemicals, and gentle heating maintains a balance between safety and quality. The integration of this material into OBE-based courses enables students to develop comprehensive competencies, from theoretical understanding to practical skills, relevant to industry demands and global food security challenges.

6.1 Chemical Methods: Natural Preservatives, GRAS Compounds

The use of chemical methods in post-harvest preservation is a growing approach in line with increasing demands for food safety and sustainability. Chemical preservatives can be divided into two broad categories: natural preservatives and Generally Recognized as Safe (GRAS) compounds. Natural preservatives are an important choice because they are derived from plant and animal sources that are acceptable to consumers, while GRAS compounds are widely used because they have passed safety evaluations by authorized agencies. Integrating these two approaches into an Outcome-Based Education (OBE) curriculum can equip students with an understanding of the basic concepts, practical applications, and regulatory implications.

Natural preservatives are gaining popularity as consumers tend to avoid synthetic ingredients associated with long-term health risks. Essential oils from plants such as cinnamon, clove, and oregano have antimicrobial properties that can inhibit the growth of pathogenic bacteria and spoilage microbes. Active compounds such as eugenol, carvacrol, and cinnamaldehyde have been shown to effectively suppress the growth of Escherichia coli and Aspergillus flavus in horticultural products. Their mechanisms of action include damage to microbial cell membranes, inhibition of metabolic enzymes, and oxidation of cellular components. The application of these natural preservatives not only extends shelf life but also enhances the functional value of products because some compounds act as antioxidants (Sharma et al., 2020).

In addition to essential oils, other plant extracts, such as phenolics from green tea and flavonoids from fruits, have also been shown to inhibit microbial activity and oxidation. These compounds work by stabilizing free radicals and preventing the degradation of natural pigments, thus maintaining product color and freshness. Nanoencapsulation technology is even being developed to increase the stability and effectiveness of these bioactive compounds during storage and distribution. Thus, natural preservatives function not only as microbial control but also as sensory enhancement agents, in line with the clean label trend in the modern food industry.

GRAS compounds include chemicals that have been determined safe for use in food based on scientific evidence and historical use. Common examples include ascorbic acid, citric acid, sodium benzoate, and potassium sorbate. These compounds function as acidity regulators, antioxidants, and antimicrobials, thereby extending the shelf life of various fresh and minimally processed products. Their application in horticultural products is typically through dipping, coating, or mixing in post-harvest solutions. The selection of the type and concentration of GRAS preservatives requires consideration of regulatory and consumer safety aspects to ensure their use remains within standards.

Ascorbic acid and citric acid are examples of GRAS compounds widely used to inhibit enzymatic browning in fruits and vegetables. Both compounds lower pH and act as reducing agents, thus inhibiting the activity of the polyphenol oxidase enzyme. Research shows that treatment with an ascorbic acid solution can slow browning in apple and potato slices without negatively affecting flavor. Meanwhile, citric acid not only prevents browning but also plays a role in maintaining the color stability of anthocyanin pigments in berries during cold storage (Ribeiro et al., 2021).

Sodium benzoate and potassium sorbate are GRAS preservatives with high effectiveness in suppressing the growth of mold and yeast. Both are widely used in fruit juices, fermented beverages, and fresh horticultural products that are susceptible to microbial contamination. These compounds work by lowering the internal pH of microbial cells and inhibiting essential enzymatic activity, thus halting cell growth. However, the use of these substances must meet the maximum residue limits set by international regulatory agencies to prevent negative effects on consumer health.

The combination of natural preservatives and GRAS compounds is beginning to be studied to create synergistic effects. For example, the combination of essential oils with ascorbic acid has been shown to be more effective in suppressing bacterial growth than either compound alone. Furthermore, the combination of polysaccharide-based edible coatings with the addition of natural and GRAS preservatives can form a double barrier that suppresses respiration and transpiration of fresh produce. This strategy shows great promise for application in modern supply chains because it can reduce the excessive use of synthetic preservatives.

The downside of using natural preservatives is the variability in active compound content due to differences in plant varieties, cultivation conditions, and extraction methods. This can impact the consistency of effectiveness in post-harvest applications. In contrast, GRAS preservatives have clearer stability and quality standards, but tend to induce microbial resistance when used repeatedly in low concentrations. Therefore, further research is focused on finding optimal formulas that combine these two types of preservatives to increase effectiveness while meeting consumer expectations for natural products.

In the context of OBE, students studying postharvest chemical preservation methods are expected to master the theoretical, technical, and regulatory aspects. They not only need to understand the biochemical mechanisms of natural and GRAS preservatives but are also required to analyze the implications of their use on product quality, food safety, and consumer acceptance. Mastery of these competencies is crucial as the global agriculture and food industry increasingly emphasizes the use of natural ingredients that are safe, sustainable, and comply with international regulations.

The integration of material on natural preservatives and GRAS compounds into an OBE-based curriculum will ultimately produce graduates who are adaptive and critical in addressing contemporary food issues. They are expected to be able to design science-based innovations to extend the shelf life of post-harvest products, reduce food loss, and support global food security. With a comprehensive understanding, students can provide practical solutions that prioritize consumer health while meeting the needs of a competitive industry.

6.1 Biotechnology Methods: Enzymes, Probiotics, Nano-Bio Coating

The use of enzymes in the context of postharvest biotechnology encompasses two main approaches: controlling endogenous enzymes that adversely affect product quality, and utilizing exogenous enzymes as functional agents to improve product stability and safety. Endogenous enzymes such as polyphenol oxidase (PPO) and peroxidase (POD) play a dominant role in the enzymatic browning process, which reduces the visual appeal and commercial value of fresh produce after mechanical injury or cutting. Therefore, mitigation strategies are directed at inhibiting these enzyme activities through chemical treatments, natural enzyme inhibitors, or manipulation of storage conditions that suppress contact between the enzyme and the phenolic substrate. On the other hand, exogenous enzymes such as pectinase, cellulase, and laccase have been explored for specific purposes, such as pectinase to modify texture in processed products to reduce losses during handling, or laccase to decolorize certain polyphenolics in preservative formulations. Omics-based approaches are now enriching the understanding of gene regulation and metabolic pathways associated with these key enzymes so that biotechnological interventions can be designed more targeted, for example by identifying the most active PPO isoforms under specific storage conditions, or by modulating genetic expression at the pre-harvest stage to reduce the potential for post-harvest browning (Wang et al., 2024).

The design and formulation of biopreservative agents containing probiotic or antagonistic microorganisms has shown strong promise as an environmentally friendly postharvest biocontrol strategy, with mechanisms of action including competition for nutrients and space, production of antimicrobial metabolites such as organic acids and volatile compounds, release of lytic enzymes that disrupt pathogen cell walls, and stimulation of host defense responses. Frequently studied candidates include several strains of non-Saccharomyces yeasts and lactic acid bacteria that not only suppress pathogen populations but can also contribute to the aromatic and nutritional profiles of certain processed products. Modern biopreservative formulations emphasize viability stability during application and distribution, making gentle drying, microencapsulation, and embedding into edible coating matrices options to maintain antagonist effectiveness on fruit or vegetable surfaces during storage and transportation. Risk and safety evaluation, including GRAS assessment for proposed strains and testing of epiphytic microbiome interactions, are mandatory components of the development of these biotechnological products for market acceptance and regulatory compliance (Comitini et al., 2023).

Nano-bio coating represents the intersection of edible biopolymer coatings and nanotechnology to create a surface layer capable of reducing mass loss, regulating gas exchange, and controlling the release of antimicrobial and antioxidant agents. Nanoemulsion and nanocomposite concepts enhance the functional stability of bioactive ingredients such as essential oils, vitamins, or natural antibacterials, thus prolonging their active release throughout shelf life. Polysaccharide-based formulations such as chitosan or alginate enriched with controlled nanoparticles have been shown to reduce respiration, maintain texture, and suppress the growth of surface pathogens on various fresh commodities. However, their successful application requires optimization of film thickness, application method (spray vs. dip), and the physical characteristics of the fruit surface. Furthermore, consumer and environmental safety are important concerns because the nanoscale nature of the bulk material can affect bioavailability and toxicity, therefore, laboratory-scale studies must be accompanied by toxicological and product life cycle studies to ensure that the technical benefits do not negatively impact human health or the environment (Oliveira Filho et al., 2021).

The integration of enzymes, probiotics, and nano-biocoatings opens up synergistic opportunities that can be exploited to design multifactorial preservation systems, a practical example is a nanocomposite edible coating containing an antimicrobial essential oil nanoemulsion while simultaneously containing encapsulated antagonistic bacteria for periodic release, accompanied by a gentle enzymatic treatment that inactivates spoilage factors without compromising nutrients. Such a combined approach allows for reduced intensity of synthetic chemical interventions while simultaneously improving shelf life and sensory quality. However, from a postharvest physiology perspective, such designs must consider the response of plant tissues to the treatment, for example, the coating's impact on O2/CO2 diffusion, which can modulate respiration and ethylene metabolism, as well as the complex interactions between probiotic microbes and the indigenous microbiota on the product surface. Therefore, a comprehensive experimental design involving physiological, microbiological, and sensory parameters is necessary to validate the effectiveness and safety of integrated biotechnological solutions.

The development of an Outcome-Based Education (OBE) curriculum for postharvest physiology and technology courses that incorporate a biotechnology component should emphasize the learning of interdisciplinary competencies: the ability to design experiments to assess the effectiveness of enzyme inhibitors, skills in the formulation and stabilization of antagonistic microorganisms, and knowledge of nanotechnology principles relevant to edible coatings. Laboratory-based learning and industrial projects will be essential so that students not only understand the theory but also are able to apply microencapsulation techniques, enzyme activity characterization, and microbiological challenge test evaluation in an industrial context. Furthermore, regulatory, ethical, and risk assessment aspects must be explicitly taught, given that postharvest biotechnology often requires approval from food regulatory agencies and long-term safety testing (Comitini et al., 2023, Oliveira Filho et al., 2021).

Technical and scientific challenges still limiting the widespread adoption of biotechnological methods include variability in biological performance under field conditions, production scale and formulation stability, and relative cost compared to conventional methods. Variation in substrate, climatic conditions, and cold chain management influence the success of probiotic or coating applications, making pre-commercialization training strategies and field trials crucial. Furthermore, advances in omics-based analytics offer opportunities to understand mechanisms of action at the molecular level and predict optimal operating conditions, for example, the integration of proteomics and metabolomics can help assess the response of fruit tissues to nanocoatings or to antagonistic enzyme activity, allowing for more prescriptive intervention design (Wang et al., 2024).

From a sustainability perspective, biotechnological methods offer added value by reducing the use of synthetic chemical insecticides and fungicides, reducing post-harvest losses, and enabling the creation of value-added products that meet consumer preferences for clean labels and natural ingredients. However, carbon footprint assessments and environmental impact analyses of the mass production of biopolymers and nanoparticles must be part of implementation studies. Economic sustainability also requires business models that take into account production costs, market value-added, and applicable regulations, training programs for small and medium-sized enterprises (SMEs) can accelerate the translation of these technologies into broader field practice.

Future prospects include the development of probiotic strains specifically selected for postharvest biocontrol roles, improved encapsulation techniques that maintain microbial viability during distribution, and the use of omics data for the design of more specific enzyme inhibitors. Furthermore, applied research testing real-world supply chain scenarios, long-term safety evaluations, and standardization of nanocoating characterization methods will accelerate commercial adoption. For educational purposes, developing an OBE module that integrates enzymology theory, applied microbiology, formulation technology, and regulatory ethics will produce graduates prepared to face the challenges of innovation in postharvest preservation technology.

6.1 Hurdle Technology

Hurdle technology in post-harvest preservation is an approach that simultaneously combines various physical, chemical, and biotechnological control methods to suppress microbial growth and extend the shelf life of products. This concept is based on the principle that microorganisms require optimal conditions to reproduce, so that by applying several barriers simultaneously, such as refrigeration, the use of natural compounds, atmospheric regulation, and the application of enzymes or probiotics, it will create conditions that are hostile to microbial growth. This strategy is more effective than using a single method, because it reduces the possibility of microbial adaptation to certain preservation conditions. Therefore, the combination of preservation technologies is seen as one of the modern solutions to address global challenges to the safety and quality of fresh produce.

The use of refrigeration as the basis for hurdle technology is often combined with modified atmosphere packaging, which can reduce the respiration rate of horticultural products while suppressing microbial activity. Lowering the temperature slows cellular metabolism, while regulating oxygen and carbon dioxide concentrations creates additional barriers that make conditions more difficult for microbes to tolerate. This combination has been shown to maintain the freshness of fruits and vegetables longer than conventional refrigeration alone. Several studies have shown that combining refrigeration with modified atmosphere packaging can extend the shelf life of tomatoes by up to two times compared to either method alone.

In addition to refrigeration, partial drying and the use of natural preservatives are also strategies within hurdle technology. For example, dried fruit with a low water content tends to be more resistant to mold growth, but when combined with the application of natural antimicrobial compounds such as ascorbic acid or plant extracts, its shelf life can be further extended. Drying reduces the water availability to microorganisms, while the natural compounds work biochemically to inhibit enzyme activity or damage microbial cell membranes. The synergy of these two methods provides a stronger, multi-layered layer of protection.

Hurdle technology also often combines mild heating with the addition of GRAS compounds. Mild heating can inactivate some microorganisms without damaging the nutritional and sensory properties of the product, while the addition of regulatory compounds such as citric acid or calcium propionate can control residual microbial growth. This combination is commonly used in fresh fruit juices and functional beverages because it maintains flavor and vitamin content better than conventional pasteurization.

In the context of biotechnology, hurdle technology can also combine probiotic applications with nano-bio coatings to create natural preservation while enhancing the functional value of products. Probiotics play a role in suppressing the growth of pathogenic microbes through nutrient competition and the production of inhibitory metabolites, while nano-bio coatings form a physical barrier that can regulate gas exchange and contain antimicrobial agents. This combination not only extends the shelf life of products but also adds health value to consumers through the presence of beneficial microbes.

One of the advantages of implementing hurdle technology is its flexibility, allowing it to be tailored to the product type and target market. For example, fresh horticultural products exported abroad require a longer shelf life, so a combination of refrigeration, modified atmosphere packaging, and biopolymer-based edible coatings is an appropriate choice. Conversely, for minimally processed products, a combination of light heating and natural preservatives can maintain sensory and nutritional quality. This flexibility makes hurdle technology relevant across various food supply chain contexts.

The application of hurdle technology also contributes to the sustainability of the food system by reducing the use of synthetic chemicals in preservation. By relying on a combination of natural and physical barriers, the use of post-harvest pesticides or synthetic preservatives can be reduced. This is crucial to meet consumer demands for healthier and more environmentally friendly food. Studies show that the combined application of bio-coating and probiotic-based technology can reduce dependence on synthetic fungicides by up to 60 percent, positively impacting production sustainability.

However, implementing hurdle technology also requires careful consideration of the interactions between the barriers used. Inappropriate combinations can lead to antagonistic effects, for example, excessively high temperatures can reduce the effectiveness of added probiotics. Therefore, research is ongoing to understand the optimal synergy between different methods to achieve preservation goals without compromising product quality. This emphasizes the importance of integrating knowledge of postharvest physiology, processing technology, and food microbiology.

Furthermore, the successful implementation of hurdle technology depends heavily on adequate infrastructure and human resource support. The use of advanced cooling technologies, modified atmosphere packaging, and nano-bio coatings require significant investment and skilled operators. Therefore, implementation in developing countries faces additional challenges, despite the significant potential benefits in reducing crop losses. Increasing post-harvest technology capacity through OBE-based education could be a solution to producing competent experts in this field.

Overall, hurdle technology represents a new paradigm in post-harvest preservation technology that prioritizes a multidimensional approach. Through a combination of physical, chemical, and biotechnological barriers, food products can be better protected from damage and contamination without having to rely on a single preservation method. This aligns with the needs of the modern food industry, which demands high quality, safety, and sustainability in global distribution systems. Therefore, hurdle technology is not just a preservation technique, but also a strategy oriented towards consumer health and environmental sustainability.

CHAPTER 8
Minimal Processing Technology

Minimal processing technology is an innovative approach in the post-harvest chain that focuses on providing fresh, ready-to-consume products while maintaining their natural qualities, particularly for fresh-cut fruits and vegetables. This concept emphasizes simple treatments such as washing, peeling, cutting, and packaging, thus maintaining freshness while making products more convenient for modern consumers. However, the application of this technology faces significant challenges in maintaining sensory quality and food safety, as the cutting process can increase respiration rates, tissue damage, and the risk of microbial contamination. To address these challenges, various supporting technologies are used, such as sanitation with natural or chemical disinfectants, the use of edible coatings that extend shelf life, and modified atmosphere packaging (MAP), which regulates the gas composition in packaging to slow deterioration. The application of minimal processing technology is becoming increasingly relevant for local commodities because it can increase added value, expand market access, and meet consumer demand for healthy and convenient products, while simultaneously encouraging the development of agro-industry based on domestic resources.

6.1 Fresh-Cut Produce Concept

The concept of fresh-cut produce is a minimally processed form that is increasingly developing in modern post-harvest chains because it offers fresh fruit and vegetable products that are ready to consume while maintaining their natural physiological characteristics. These products usually undergo basic treatments such as washing, peeling, cutting, and packaging without undergoing intensive thermal processing stages, thus maintaining freshness, taste, and nutritional value. The advantage of this concept is its ability to provide practical, nutritious food that is in line with the lifestyle of modern society, which tends to desire the convenience of consuming fresh produce every day. However, behind its advantages, fresh-cut produce faces significant challenges in terms of physiological and microbiological control because the cutting process triggers increased respiratory activity and susceptibility to tissue damage.

Fresh-cut produce is not only required to maintain visual qualities such as color, texture, and aroma, but also to maintain the stability of its nutritional content, which is a key selling point. The cutting process of fruits and vegetables releases nutrient-rich cellular fluids, which in turn increases the risk of microbial growth. This makes effective sanitation and packaging crucial for maintaining product quality and safety. According to Otoni et al. (2021), proper post-harvest treatment of fresh-cut produce can slow quality deterioration, maintain physiological activity, and extend shelf life.

One important physiological characteristic of fresh-cut produce is an increased respiration rate due to plant tissue damage. High respiration rates accelerate energy substrate consumption, accelerate wilting, and degrade sensory quality quickly. Therefore, controlling the respiration rate is a key focus of this concept by maintaining low storage temperatures, using modified atmosphere packaging, and applying protective coatings based on natural ingredients. According to Ragaert et al. (2020), integrated physiological control can extend shelf life while maintaining quality attributes such as crispness and color in fresh-cut produce.

Food safety is a primary concern in the fresh-cut produce concept because the peeling and cutting processes open up the potential for cross-contamination from equipment surfaces, workers, and the processing environment. Pathogenic microorganisms such as Escherichia coli, Salmonella, and Listeria monocytogenes are frequently reported as potential contaminants in these products, making adequate sanitation crucial. The use of chlorine-based disinfectant solutions, organic acids, and natural antimicrobial compounds can help reduce the number of surface microbes. Therefore, sanitation technology is an integral supporting pillar of the implementation of fresh-cut produce.

In addition to microbiological safety, nutritional aspects are also important factors influencing consumer acceptance of fresh-cut produce. The vitamin C, phenolic, and other antioxidant content of fresh fruits and vegetables is highly sensitive to mechanical damage and oxidation. Minimal processing often results in faster nutrient loss compared to whole produce due to increased oxygen exposure to exposed tissues. To address this, modified atmosphere packaging (MAP) strategies are used, which regulate oxygen and carbon dioxide levels within the package, slowing oxidative reactions and maintaining the stability of bioactive compounds.

Fresh-cut produce is also closely linked to modern consumer preferences, which demand practical, hygienic products with a long shelf life. Therefore, innovations in packaging technology, coatings, and the addition of natural compounds with antibacterial effects are constantly being developed. For example, polysaccharide- or protein-based edible coatings combined with plant extracts can provide dual protection, slowing water loss and suppressing microbial growth. This demonstrates that the concept of fresh-cut produce relies not only on basic physical treatments but also requires an integrative approach based on supporting technology.

From an economic perspective, developing fresh-cut produce can provide significant added value to horticultural products, particularly in developing countries with abundant fruit and vegetable production. With minimal processing, local products can be marketed in ready-to-eat form, expanding distribution reach and increasing competitiveness in both domestic and international markets. According to James and Ngarmsak (2022), post-harvest innovation through fresh-cut produce can support market diversification while reducing crop losses due to limitations of conventional storage.

Implementing the fresh-cut produce concept on an industrial scale requires strict operational standards, from raw material selection and hygienic handling to final packaging. The fruits and vegetables used must be of the highest quality, free from mechanical damage, and possess sufficient physiological resilience. These factors significantly determine the product's shelf life and market success. Furthermore, training the workforce in proper sanitation and hygiene practices is crucial to reducing the risk of contamination during the production process.

On the other hand, the successful implementation of the fresh-cut produce concept depends not only on technology but also on consumer education regarding product storage and handling after purchase. Consumers need to understand that these products remain susceptible to damage and must be stored at low temperatures to maintain quality. This underscores the importance of synergy between producers, regulators, and consumers in maintaining product quality throughout the supply chain. This way, the fresh-cut produce concept can operate optimally and benefit all parties.

Thus, the fresh-cut produce concept can be viewed as a strategic solution to meet the need for healthy, nutritious, and practical food for modern society. Further development in storage technology, sanitation, and environmentally friendly packaging will further strengthen the competitiveness of this product. In the future, this concept has great potential for wider application, including for local fruit and vegetable commodities with high economic value, thereby contributing to food security and the development of the national agro-industry.

6.1 Quality and Safety Challenges

The main challenge in maintaining the quality of fresh-cut produce lies in the physiological changes that occur immediately after cutting. Cutting fruit and vegetable tissue increases respiration and transpiration rates, as well as the release of destructive enzymes, which accelerate the degradation of texture, color, and aroma. This phenomenon not only reduces sensory quality but also shortens shelf life, requiring special handling strategies to minimize post-harvest damage triggered by mechanical stress.

In addition to physiological factors, microbial contamination is also a serious issue with fresh-cut produce because exposed tissue surfaces provide a nutrient-rich substrate for the growth of pathogenic and spoilage bacteria. This situation increases the risk to food safety, especially if handling is unhygienic or storage temperatures are uncontrolled. Therefore, strict control of sanitation, processing, and distribution is crucial to maintaining the safety of minimally processed products.

Another frequently encountered quality challenge is color changes caused by phenolic oxidation, for example, in apples or potatoes, which undergo rapid enzymatic browning after cutting. This change reduces consumer acceptance, although nutritional value remains relatively intact. Enzyme inhibitor technologies such as ascorbic acid or natural coatings can help suppress browning reactions, but their effectiveness is limited for certain commodities.

Loss of freshness is also a significant issue because cutting accelerates water evaporation from the tissue, leading to rapid wilting of the product. Suboptimal relative humidity during storage exacerbates this physical decline. Therefore, humidity-controlled packaging and the use of coating materials can be a solution to maintain plant cell turgor.

The safety of fresh-cut produce is affected not only by microorganisms but also by chemical residues used for sanitation or preservation. Strict regulations on the use of food-grade chemical compounds must be implemented to prevent potential toxicological hazards. The principle of using GRAS (Generally Recognized As Safe) compounds is an important approach to ensuring food safety while maintaining product quality.

Furthermore, cold chain distribution plays a crucial role in maintaining the quality and safety of fresh-cut produce. Even brief disruptions in storage temperature can accelerate microbial growth and exacerbate physiological deterioration. Therefore, maintaining consistently low temperatures from post-harvest to end-consumer is a key challenge in minimal processing systems.

Limitations in packaging technology also affect the success of maintaining fresh-cut quality. While modified atmosphere packaging (MAP) technology can extend shelf life, inappropriate gas composition can lead to problems such as ethanol accumulation due to anaerobic fermentation. Further research is needed to find suitable gas formulations for various types of local fruits and vegetables with varying respiratory characteristics.

Sensory aspects such as texture and aroma are often more difficult to maintain than nutritional content. Consumers tend to judge product quality based on visual appearance and taste, so even small changes can reduce market appeal. Therefore, innovations in the use of nanotechnology-based coatings or probiotics are solutions being developed to maintain sensory quality without compromising health.

On the other hand, implementing international quality and safety standards such as HACCP and ISO 22000 remains a challenge in many developing countries. Limited infrastructure, costs, and technical knowledge make the implementation of quality assurance systems less than optimal. This impacts the limited access of fresh-cut products to export markets that demand high food safety standards.

Overall, the quality and safety challenges of minimal processing require a synergy between understanding post-harvest physiology, the development of innovative technologies, and strict regulations. This combination of factors is crucial for the success of fresh-cut products in meeting consumer expectations for healthy, safe, and convenient food, while also opening up opportunities to increase the competitiveness of local agro-industries in the global market (Barrett, 2021, James & Ngarmsak, 2020, Siddiqui, 2022).

6.1 Supporting Technologies: Sanitation, Coating, MAP

Sanitation is a crucial initial step in the horticultural post-harvest chain. This process aims to reduce or eliminate pathogenic and spoilage microorganisms that can accelerate product deterioration. Commonly used sanitation methods include washing with chlorine solutions, ozone, or organic acids such as peracetic acid. It is important to note that the effectiveness of sanitation is highly dependent on the concentration and duration of contact of the active ingredient, as well as the temperature and pH of the solution. Research by Siddiqui and Rahman (2015) shows that proper sanitation can reduce the microbial load on fresh and ready-to-eat produce, thereby extending shelf life without significantly reducing sensory quality.

After the sanitation process, coating is the next important step. Coating aims to form a protective layer on the product surface, which can reduce water loss, slow respiration, and inhibit microbial growth. Commonly used coating materials include polysaccharides, proteins, and lipids, which can be edible or non-edible. According to research by Zdulski et al. (2024), the use of polysaccharide-based edible coatings such as chitosan or alginate can increase product resistance to mechanical damage and extend the shelf life of fresh and fresh-cut products.

Furthermore, coatings can act as a barrier against ethylene gas, a plant hormone that accelerates ripening and spoilage. Thus, coatings play a role not only in maintaining the physical quality of the product but also in controlling the biochemical processes that occur post-harvest. However, it is important to choose a coating material that is not only effective in extending shelf life but also safe and does not negatively alter the product's organoleptic properties.

Modified atmosphere packaging (MAP) is a technology used to alter the gas composition within a package to slow the respiration process and extend the product's shelf life. This technology involves regulating oxygen (O2) levels.), carbon dioxide (CO), and nitrogen (N) in packaging according to the specific needs of the product. For example, for products that are sensitive to oxygen, the Ocan be reduced, while COenhanced to inhibit microbial growth. According to research by Zdulski et al. (2024), the combination of edible coating and MAP can provide a synergistic effect in extending the shelf life of fresh and fresh-cut products.

However, implementing MAP requires special attention to the compatibility of packaging materials and products, as well as the management of storage conditions such as temperature and humidity. Incorrect settings for these parameters can lead to the formation of undesirable atmospheres, which can accelerate product deterioration. Therefore, it is important to regularly test and monitor the condition of the packaging and product during storage.

In the context of Outcome-Based Education (OBE), a thorough understanding of these supporting technologies is crucial for students. Through the OBE approach, students are not only taught theory but also engaged in hands-on practice, enabling them to understand and apply these technologies in real-world contexts. This will prepare them to face challenges in the post-harvest industry and contribute to the development of more efficient and environmentally friendly technologies.

Furthermore, the integration of theory and practice within the OBE curriculum encourages students to think critically and innovatively. They are encouraged to evaluate various existing technologies, weigh their advantages and disadvantages, and design solutions tailored to specific product needs and local conditions. This approach is expected to produce graduates who possess not only technical knowledge but also sound problem-solving and decision-making skills.

Overall, supporting technologies such as sanitation, coating, and MAP play a crucial role in maintaining the quality and freshness of post-harvest products. Proper and efficient application of these technologies can extend product shelf life, reduce waste, and increase consumer satisfaction. Therefore, it is crucial for educational institutions to integrate these topics into their curricula to equip students with the necessary competencies to face the challenges of the post-harvest industry.

Thus, through the OBE approach, students gain not only theoretical knowledge but also practical skills that can be directly applied in the field. This aligns with the goal of higher education to produce graduates who are prepared to face the dynamics of industry and contribute to the sustainable development of the agriculture and food sectors.

6.1 Application to Local Fruits and Vegetables

The application of minimal processing technology to local fruits and vegetables is an innovative approach that seeks to maintain the freshness, nutritional value, and sensory quality of horticultural products, while meeting consumer demand for convenient, ready-to-eat products. The main challenge in minimal processing is maintaining the cellular and biochemical integrity of the product, which is susceptible to mechanical damage, microbial contamination, and enzymatic changes after harvest. Therefore, a thorough understanding of the specific postharvest physiology of each type of local commodity is required. For example, tropical fruits such as mango, snake fruit, and rambutan have different physiological characteristics than leafy vegetables such as spinach and kale. The successful application of this technology depends heavily on a series of integrated postharvest treatments, from optimal raw material selection to appropriate packaging.

Raw material selection is a crucial step in minimal processing technology. The initial quality of fruits and vegetables directly determines the shelf life of the final product. Based on postharvest physiology principles, selected commodities must be at the appropriate level of ripeness, free from physical defects, and show no signs of damage from pests or diseases. Climacteric fruits such as mangoes and bananas harvested at physiological maturity still have the potential to continue ripening, while non-climacteric fruits such as oranges and strawberries must be harvested at optimal ripeness for consumption. Therefore, understanding respiration rates, ethylene production, and transpiration is fundamental to determining effective postharvest handling strategies (Susanto, 2018).

After selecting the raw materials, the processing steps include, at a minimum, washing, peeling, and sanitizing. Washing removes impurities and reduces the initial microbial load. The water used must meet strict quality standards and is often supplemented with sanitizing agents such as chlorine or ozone. Peeling and cutting must be performed quickly and with sharp tools to minimize tissue damage, which can trigger enzymatic browning and the release of volatile compounds. This speed is crucial to maintain low product temperatures, which can slow post-harvest metabolic rates.

Any mechanical treatment of fruits and vegetables causes post-harvest stress, which triggers physiological responses such as increased respiration and the production of phenolic compounds. This phenomenon often results in enzymatic browning, an undesirable browning, particularly in fruits and vegetables high in polyphenols, such as apples, potatoes, and bananas. To overcome this, dipping with natural antioxidant solutions, such as ascorbic acid (vitamin C) or citric acid, which act as polyphenol oxidase (PPO) inhibitors, is often used.

Controlling microbial growth is a major challenge in minimal processing technologies. Chlorine-, peroxide-, or ozone-based sanitizing solutions are often used to clean product surfaces, but their use must be carefully regulated to avoid harmful residues. As a more environmentally friendly alternative, many studies have begun exploring the use of natural ingredients such as essential oils, spice extracts, or lactic acid bacteria as antimicrobial agents (Handayani & Rachmat, 2020). The use of these additives aims not only to extend shelf life but also to enhance the nutritional and sensory profiles of products.

Applying this technology to local fruits and vegetables faces unique challenges, such as the availability of diverse local varieties, a lack of post-harvest standardization, and inadequate cold chain infrastructure. However, this also opens up significant opportunities for developing value-added products. For example, durian and jackfruit can be processed into ready-to-eat products, while tropical vegetables like cassava and sweet potatoes can be packaged in chunks for easier processing. Thus, minimal processing technology can be key to increasing the competitiveness and economic value of local commodities in both domestic and international markets.

Packaging plays a vital role in minimal processing technology. Modified atmosphere packaging (MAP) is often used to create an optimal environment around the product by regulating the levels of oxygen, carbon dioxide, and nitrogen. This aims to suppress the respiration rate and growth of aerobic microorganisms, thereby extending the product's shelf life. Furthermore, effective cold chain management, from the slaughterhouse to the point of sale, is essential to maintaining product quality. Without strict temperature control, all efforts made in the initial process will be wasted.

Food safety is a non-negotiable aspect of minimal processing technology. Pre-cut products are at higher risk of microbial contamination due to exposed cell surfaces. Therefore, strict hygiene standards must be implemented at every stage of production, from equipment sanitation and worker hygiene to factory environmental conditions. Compliance with international food safety standards, such as HACCP (Hazard Analysis and Critical Control Points), is essential to ensure the products are safe for consumption.

By adopting minimal processing technology, local farmers can gain added value from their crops. Properly processed and packaged products command higher selling prices than fresh produce. This can help improve farmers' welfare and encourage rural economic diversification. Furthermore, this technology can help reduce post-harvest losses, which are often a serious problem for local commodities due to their perishable nature.

The future of minimal processing technology for local fruits and vegetables is very promising. Future research could focus on developing new, more environmentally friendly technologies, such as the use of UV radiation or cold plasma for surface sterilization. Furthermore, exploring local varieties that are more resistant to processing, as well as developing more effective and safe anti-browning and antimicrobial solution formulations, will be important research areas. Collaboration between academia, industry, and farmers will be key to realizing the full potential of this technology (Rahardjo, 2021).

CHAPTER 9
Post-Harvest Food Quality and Safety Standards

The application of post-harvest physiology and technology in the modern horticultural industry is not only focused on maintaining the physical quality of products but also requires adherence to stringent quality and food safety standards. This paragraph will examine the various crucial aspects that shape this regulatory framework, starting with the national framework through the Indonesian National Standard (SNI), which establishes quality specifications and safety requirements for domestic horticultural products. Furthermore, it will discuss the relevance of international regulations, such as those established by Codex Alimentarius, the International Organization for Standardization (ISO), and Hazard Analysis and Critical Control Points (HACCP), which serve as global benchmarks for ensuring horticultural products can compete in the international market. Furthermore, we will explore the importance of labeling and traceability as instruments to provide accurate information to consumers and enable product traceability in the event of food safety issues. We will also highlight ethical and sustainability aspects in the post-harvest supply chain, which include responsible production practices, fairness to farmers, and minimizing environmental impact.

6.1 Indonesian National Standard (SNI) for Horticultural Products

Amidst increasingly fierce market competition and growing consumer awareness of the importance of food safety, the implementation of the Indonesian National Standard (SNI) for horticultural products has become a crucial element in the post-harvest supply chain. SNI serves as an official benchmark that establishes minimum requirements for product quality, safety, and specifications. This standard not only protects consumers from substandard products but also helps producers and businesses ensure that their products meet certain criteria, thereby facilitating trade and increasing market confidence. Compliance with SNI demonstrates a commitment to quality, which in turn can increase the competitiveness of local horticultural products in both domestic and international markets.

The development of SNI for horticultural products involves a comprehensive series of processes, starting with in-depth research into the post-harvest physiological characteristics of each commodity. Various physiological aspects, such as respiration rate, ethylene production, and nutrient composition, form the basis for determining quality standards. For example, the SNI for bananas regulates ripeness levels, freedom from physical defects, and tolerance limits for certain defects, all based on an understanding of how bananas react after harvest. This standard ensures that products reaching consumers have optimal shelf life and consistent quality.

One of the main focuses of SNI is food safety. This includes maximum limits on pesticide residues, microbiological contaminants, and permitted food additives. These regulations aim to protect consumer health from potential hazards that may arise from improper agricultural practices or post-harvest handling. For example, SNI 01-3141-1992 for chili peppers regulates limits on pesticide residues and other contaminants. Rigorous laboratory testing is required to verify that horticultural products meet these safety standards, making it an essential prerequisite for SNI certification.

Effective post-harvest management plays a central role in achieving and maintaining SNI standards. Practices such as proper harvesting, careful handling to avoid physical damage, and the use of appropriate storage technologies all contribute to meeting established quality standards. The cold chain, for example, is crucial for perishable commodities like strawberries and leafy greens, as controlled temperatures can slow the rate of degradation and microbial growth, thus keeping products fresher for longer. Proper implementation of these technologies allows products to maintain their quality attributes in accordance with SNI requirements.

The implementation of SNI also provides significant economic benefits for farmers and the industry. With SNI certification, horticultural products can command higher selling prices, expand market access, and build a reputation for quality. This encourages farmers to adopt better agricultural practices and standardized post-harvest handling, creating a continuous cycle of quality improvement. Compliance with standards also reduces post-harvest losses, which are often a significant problem in the agricultural sector.

Despite its importance, SNI implementation faces several challenges on the ground, particularly for small-scale farmers. These challenges include high certification costs, a lack of understanding of standard procedures, and limited access to the necessary technology and infrastructure. Therefore, support from the government and relevant institutions in the form of training, subsidies, and technical guidance is needed to facilitate farmers in meeting SNI requirements. Collaboration between various parties is key to ensuring wider SNI adoption.

SNI quality standards encompass not only physical attributes but also sensory qualities such as taste, aroma, and texture. These criteria are crucial because they directly influence consumer preferences. SNI for fruits like mango and avocado often include requirements related to sweetness level (based on Brix), flesh firmness, and ideal skin color. Organoleptic testing and scientific instruments are used to ensure consistent sensory quality, ensuring a satisfying experience for consumers (Adityawati & Prameswari, 2020).

The correlation between SNI and international regulations is very close. Many SNI standards have been adopted or aligned with international standards, such as those established by Codex Alimentarius or the International Organization for Standardization (ISO). This facilitates the export of Indonesian horticultural products to global markets. By complying with SNI, businesses have indirectly taken the first step toward meeting stricter international market requirements, paving the way for more efficient and reliable global trade.

Education and outreach regarding SNI are crucial components in encouraging compliance. Higher education curricula, such as courses in physiology and post-harvest technology, play a strategic role in introducing students and prospective agricultural professionals to the importance of these standards (Prasetio, 2022). By incorporating SNI as an integral part of the learning materials, graduates are expected to have a strong understanding of quality and safety standards and be able to apply them in industry practice.

Ultimately, the Indonesian National Standard (SNI) for horticultural products is more than just a set of technical regulations, it reflects a nation's commitment to quality, food safety, and economic competitiveness. By continuously raising awareness, facilitating implementation, and aligning with global trends, SNI will continue to be a vital instrument in bridging the gap between farm-level production and modern market demands (Setyawan, 2021). Consistent implementation will ensure that Indonesian horticultural products are not only high-quality but also safe and trusted by consumers everywhere.

6.1 International Regulations (Codex, ISO, HACCP)

International regulations play a crucial role in ensuring post-harvest food quality and safety standards, particularly for globally traded horticultural products. Three key frameworks, Codex Alimentarius, the International Organization for Standardization (ISO), and Hazard Analysis and Critical Control Points (HACCP), provide comprehensive guidance that transcends national borders. These frameworks aim not only to protect consumer health from the risks of contamination and unsuitable products, but also to create a level playing field for international trade by harmonizing standards across countries.

Codex Alimentarius, often referred to as the "Golden Book" of food safety, is a collection of standards, guidelines, and codes of practice developed jointly by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO). Codex standards cover a wide range of aspects, including pesticide residues, contaminants, food additives, and analytical methods. Compliance with these standards is crucial for countries wishing to export horticultural products. For example, Codex standards for tropical fruits like mangoes establish quality criteria, including ripeness, freedom from disease, and maximum chemical residue limits, which serve as a reference for importers and exporters worldwide.

International Organization for Standardization (ISO), while not specifically focused on food, offers a range of quality management standards that are highly relevant to the post-harvest industry. ISO 9001, for example, is a quality management system standard that can be applied to ensure consistency across all production and handling processes, including post-harvest activities. ISO 22000, on the other hand, is specifically designed for food safety management systems, integrating HACCP principles with a general management approach. By adopting ISO standards, companies can demonstrate their commitment to quality and safety, which can boost the trust of consumers and international business partners.

Among these regulations, Hazard Analysis and Critical Control Points (HACCP) is a prevention-oriented system for identifying, evaluating, and controlling hazards significant to food safety. HACCP operates based on seven basic principles, ranging from hazard analysis to establishing corrective actions and verification. In the post-harvest context, the HACCP system can be applied at every stage, from washing and cutting to packaging and storage, to prevent microbial, physical, or chemical contamination. For example, a critical point in the minimal processing of leafy vegetables might be the washing step with sanitized water to control pathogenic bacteria.

Implementing HACCP and ISO standards has a direct impact on efficiency and profitability. By minimizing food safety risks, companies can reduce costly product recalls and avoid regulatory fines. Furthermore, HACCP or ISO certification is often a mandatory requirement for supplying products to key markets in Europe, North America, and East Asia. Without this certification, market access is severely limited. Therefore, investing in these systems is not simply a matter of compliance but a fundamental business strategy.

The link between international regulations and post-harvest technology is very close. Technologies such as Modified Atmosphere Packaging (MAP) and temperature-controlled processing (cold chain) not only extend shelf life but also help meet quality standards set by Codex and ISO. For example, by controlling the atmosphere inside the packaging, the respiration rate can be reduced, thus maintaining freshness and meeting strict quality criteria. The use of these technologies, when managed within the HACCP system, can ensure that products are not only of high quality but also safe from microbial contamination.

This regulation also requires a robust traceability system. Traceability is the ability to trace a product through all stages of production, processing, and distribution. International standards, such as ISO 22005, provide guidance for establishing this system. With traceability, if a food safety issue arises, contaminated products can be quickly identified and removed from circulation, minimizing risks to public health. This system also serves to prove the product's origin and production methods, which is increasingly sought after by consumers who are conscious about the origin of their food.

The main challenges in adopting international regulations are their cost and complexity, especially for producers in developing countries. Significant investments in infrastructure, equipment, and training are required. These limited resources often hinder Micro, Small, and Medium Enterprises (MSMEs) from competing in the global market. Therefore, support from governments and non-governmental organizations in the form of technical guidance and financial assistance is crucial to facilitate the adoption of these standards (Sumarno, 2019).

Despite their differences, Codex, ISO, and HACCP complement each other and work together to create a safer and more reliable global food environment. Codex establishes specific food standards, ISO provides a broader management framework, and HACCP offers a practical methodology for controlling food safety hazards. The synergy between the three enables companies to build robust quality and food safety management systems, from end-to-end.

The implementation of these international regulations is not only about compliance but also part of an ethical commitment to global consumers. This reflects the producers' responsibility to provide products that are not only high-quality but also safe for consumption (Fatimah, 2021). Going forward, with the increasing integration of global markets, understanding and implementing these standards will be an absolute prerequisite for the sustainability and growth of the post-harvest horticultural industry, as emphasized in much academic literature (Prihatini, 2020).

6.1 Product Labeling and Traceability

In the modern era, where consumers are increasingly critical and aware of the origins of the products they consume, labeling and traceability have become integral components of effective post-harvest management. Both serve as an information bridge between producers and consumers, providing transparent data on a product's journey from farm to plate. Accurate labeling not only provides basic product information, such as name, weight, and expiration date, but can also include other important details such as variety, growing method, and certification. Meanwhile, traceability allows for product traceability in the event of a problem, allowing food safety issues to be addressed quickly and appropriately.

Horticultural product labeling, in accordance with postharvest physiology principles, must include relevant information to maintain product quality. For example, labels on tropical fruit packaging might include the harvest date, packing date, and recommended storage temperature. This information is crucial because the product's respiration and transpiration rates are highly dependent on ambient temperature. By providing clear storage guidelines, labels help consumers maintain product quality, ultimately reducing food waste. Furthermore, labels can include nutritional information, helping consumers make healthier choices.

Traceability implementation begins at the harvest stage. Each lot of produce must be assigned a unique identifier, often in the form of a barcode or QR code. This code records critical data such as the farm location, harvest date, and farmer's name. This data is then integrated into a computerized management system. This way, every unit of produce sold can be traced back to its source. For example, if a supermarket receives a complaint about moldy potatoes, the traceability system can be used to identify that lot and pinpoint the root cause of the problem throughout the supply chain.

Post-harvest physiology plays a crucial role in traceability systems. Physiological data, such as sugar content or firmness at harvest, can be recorded as part of traceability data. This information helps manage the cold chain and predict shelf life. For example, fruit harvested at different stages of ripeness will have different shelf lives. By recording these ripeness levels in the traceability system, distributors can manage inventory more efficiently and ensure that riper produce is sold first.

Labeling and traceability also form the foundation for value-added marketing. Organic horticultural products, for example, must have clear labels and a traceability system that can verify the "organic" claim. This provides added value to consumers who are willing to pay more for products produced sustainably and without harmful chemicals. In international markets, certifications such as GlobalGAP also often require robust traceability systems as part of their audits (Puspitasari, 2021).

Today's sophisticated traceability systems often utilize blockchain technology. This technology provides a decentralized and immutable database that records every movement of a product along the supply chain. With blockchain, consumers can scan a QR code on a label and gain access to the product's complete history, from seed origin to post-harvest treatment to shipping date. This creates an unprecedented level of transparency and helps build strong trust between producers and consumers.

Labeling is not only for information, but also for safety. Labels must comply with food safety regulations, such as those established by the Codex Alimentarius or other national standards, which regulate the use of food additives, allergens, and expiration dates.

Failure to comply with labeling standards can result in legal sanctions and product recalls. Therefore, it is crucial for manufacturers to ensure that all information on their product labels is accurate and complies with applicable regulations.

From an ethical perspective, transparent labeling empowers consumers to make responsible choices. Consumers can choose products produced by farmers practicing fair labor practices or those using environmentally friendly farming methods. Labels that include this information help support farmers and producers committed to sustainable practices. Thus, labeling is not just a technical tool, but also an instrument for driving positive change in the global food system.

Developing an effective labeling and traceability system requires investment in both technology and human resources. Training farmers and post-harvest workers is crucial to ensure they understand the importance of accurate data recording from the outset. The government and relevant institutions have a vital role to play in providing infrastructure and technical guidance to facilitate the adoption of this technology, especially for small-scale farmers who may lack adequate resources (Wijaya, 2020).

Overall, labeling and traceability are integral elements of modern post-harvest management focused on quality and safety. They work together to provide transparency, build trust, and improve supply chain efficiency. By continuously developing technology and harmonizing regulations, this system will further strengthen the position of horticultural products in both domestic and global markets, while meeting consumer demands for accurate information and safe products (Susilo, 2018).

6.1 Ethical and Sustainability Aspects

In addition to the focus on improving product quality and safety, post-harvest physiology and technology are increasingly facing demands to consider ethical and sustainability aspects. This shift is driven by global awareness of the environmental and social impacts of the food supply chain. Ethics, in this context, encompasses fairness for farmers and workers, while sustainability focuses on waste minimization, resource efficiency, and mitigating negative environmental impacts. Integrating these two aspects is not an option but a necessity to ensure the responsible and long-term growth of the horticultural industry.

Ethical aspects begin with fair post-harvest handling practices. Farmers, the first link in the supply chain, are often vulnerable to price fluctuations and unfair trade practices. Post-harvest technologies, such as cold storage units or simple packaging facilities, can help smallholder farmers extend the shelf life of their produce, giving them greater bargaining power and access to more profitable markets. This directly contributes to improving the economic well-being of farmers, a key pillar of ethical food production.

Beyond farmers, the working conditions of workers in post-harvest facilities are also an ethical concern. This includes issues such as fair wages, fair working hours, and safe and hygienic working conditions. The implementation of automation and ergonomic technologies not only increases efficiency but can also reduce the risk of injury and heavy physical workloads for workers. Social audits and third-party certifications, such as those related to fair trade standards, are increasingly becoming prerequisites for companies seeking to enter socially sensitive global markets.

One of the biggest sustainability challenges in post-harvest supply chains is food loss and waste. Globally, an estimated one-third of all food produced is lost or wasted each year. Post-harvest physiology and technology play a central role in addressing this issue by extending product shelf life and maintaining quality. Strategies such as precise temperature management, optimal packaging, and careful handling can significantly reduce losses between farm and consumer (Wibowo & Nugroho, 2020).

Sustainable post-harvest technologies also seek to minimize the environmental footprint. This includes efficient water use for product washing and cooling, as well as reduced energy consumption in cold storage units. The use of renewable energy sources, such as solar panels, to operate post-harvest facilities is one promising innovation for reducing carbon emissions. Furthermore, responsible sanitation practices must be ensured to prevent wastewater from the washing process from contaminating the environment.

The use of packaging materials also has significant sustainability implications. Commonly used post-harvest packaging, such as single-use plastics, contributes to pollution problems. Sustainability efforts in this sector are driving innovation in the development of recyclable, compostable, or biodegradable packaging materials. However, the choice of packaging materials must still take into account their function in protecting the product from damage and maintaining quality, so as not to compromise food safety for environmental sustainability.

In addition to packaging materials, the use of chemicals such as fungicides or coating waxes also needs to be evaluated from a sustainability and ethical perspective. These chemical residues not only pose a potential health risk to consumers but can also pollute the environment. Therefore, current research and development focuses on natural alternatives, such as plant extracts or physical treatments (e.g., UV radiation) that are effective in controlling microbial growth without leaving harmful residues.

The concept of a circular economy is increasingly relevant in the post-harvest context. Rather than discarding agricultural waste such as fruit peels, stalks, or leaves, technology can transform them into value-added products. For example, orange peels can be processed into essential oils, banana peels can be made into flour, and vegetable scraps can be fermented into animal feed or compost. This approach not only reduces waste but also creates new revenue streams for the industry (Lestari & Purnomo, 2019).

Consumers play a crucial role in driving ethical and sustainable practices. Through their purchasing decisions, consumers can send a powerful signal to industry to adopt higher standards. The availability of transparent information through labels and traceability systems enables consumers to make responsible choices, for example by choosing products that are certified organic, fair trade, or have a low carbon footprint. Educating consumers about the importance of these aspects is integral to a sustainable food ecosystem.

Thus, integrating ethical and sustainability aspects into post-harvest physiology and technology is not just a passing trend, but an inevitability. Universities, through OBE-based curricula, have a responsibility to train students to have a holistic understanding of these issues. Future graduates must not only master post-harvest techniques to maintain quality, but also be able to design supply chain systems that are socially just and environmentally responsible (Hartono & Sanjaya, 2018).

CHAPTER 10
Locally Based Post-Harvest Innovation

Postharvest physiology and technology have evolved rapidly, and this chapter will shift the focus to innovations rooted in local contexts, combining traditional knowledge with modern scientific approaches. This introduction will explore innovative strategies tailored to specific challenges and opportunities in Indonesia, beginning with a discussion of the use of local natural materials such as plant extracts, liquid smoke, and essential oils as safer and more environmentally friendly alternatives to synthetic preservatives. Furthermore, the chapter will outline simple technologies specifically designed to be accessible and applicable to farmers and Micro, Small, and Medium Enterprises (MSMEs), the backbone of the agricultural sector. We will also investigate how the application of digital technologies, such as the Internet of Things (IoT) and smart farming, is revolutionizing postharvest efficiency and traceability. We conclude by analyzing successful cases of postharvest innovation in Indonesia that have increased the added value and competitiveness of local commodities in both domestic and global markets.

10.1 Utilization of Local Natural Ingredients as Preservatives (Plant Extracts, Liquid Smoke, Essential Oils)

Amid the global trend toward more natural and sustainable food products, the use of local natural ingredients as preservatives has become a key focus in post-harvest innovation. Indonesia, with its abundant biodiversity, has great potential to develop natural preservatives from readily available plant resources. This approach not only offers a safer alternative to synthetic preservatives but can also increase the economic value of local commodities and reduce dependence on imported chemicals. This innovation is based on a deep understanding of the physiological properties of horticultural products and how bioactive compounds from nature can inhibit post-harvest degradation.

Plant extracts are a very promising source of natural preservatives. Many Indonesian plants, such as betel leaves, turmeric, galangal, and lemongrass, contain powerful antimicrobial and antioxidant compounds. For example, curcumin in turmeric and eugenol in cloves have been shown to be effective in inhibiting the growth of bacteria and fungi that cause spoilage. These extracts can be applied as dipping solutions or integrated into packaging to extend the shelf life of fruits and vegetables and maintain their sensory and nutritional qualities.

Essential oilExtracted from various plant parts such as flowers, leaves, and fruit peels, essential oils also possess potent antimicrobial properties. Essential oils from citronella, clove, or cinnamon, for example, contain volatile components that can suppress the growth of microorganisms. These oils can be sprayed onto product surfaces or vaporized in storage to create an atmosphere that inhibits microbial activity. The advantage of essential oils is their effectiveness in small doses, although careful attention to concentration is essential to avoid significantly altering the aroma and flavor profile of the product.

In addition to plant extracts and essential oils, liquid smoke is also an interesting innovation in locally based post-harvest preservation technology. Liquid smoke is produced from the pyrolysis of biomass materials, such as coconut shells or wood, and contains phenolic compounds with antimicrobial and antioxidant properties. Liquid smoke can be used for washing or dipping horticultural products to control pathogens and slow down the enzymatic browning process. The use of liquid smoke can also impart a distinctive aroma that can enhance the appeal of products, such as dried fruits or processed vegetables.

The development of natural preservatives relies heavily on an understanding of post-harvest physiology. Bioactive compounds from natural ingredients work by inhibiting enzymes that accelerate product deterioration, such as polyphenol oxidase (PPO), which causes browning, or by damaging the cell membranes of microorganisms. Understanding these mechanisms of action is crucial for designing effective and safe formulations, as well as determining optimal dosages and application methods.

The application of this innovation is not limited to technology but also involves economic and social aspects. Utilizing local natural materials can open new business opportunities for farmers and MSMEs to produce extracts or essential oils. This creates a shorter and fairer value chain, where farmers sell not only raw commodities but also processed products with higher added value. Thus, this innovation contributes to rural economic diversification and local community empowerment (Santoso & Kurniawan, 2021).

Despite its promise, the use of natural ingredients as preservatives also faces several challenges. Their effectiveness can vary depending on the plant variety, extraction method, and storage conditions. Furthermore, standardizing natural preservative products remains a challenge, as the concentration of active compounds can fluctuate. Therefore, further research is needed to develop consistent extraction methods and stable formulations to ensure consistent effectiveness.

Regulation and certification are also crucial aspects in the development of natural preservatives. To compete in the market, products using natural preservatives must meet national and international food safety standards. This includes testing for toxicity and product stability. Collaboration between academia, industry, and government is crucial to formulate clear standards and facilitate the certification process, ensuring widespread consumer acceptance of products (Wahyudi & Wijaya, 2020).

Ethically, the use of locally sourced natural preservatives offers significant benefits. This aligns with consumer demand for "clean" and "natural" products and supports sustainable agricultural practices. By reducing reliance on synthetic chemicals that can have negative environmental impacts, this innovation helps mitigate the risk of soil and water pollution and protects biodiversity.

Overall, the use of local natural ingredients as post-harvest preservatives reflects a paradigm shift from approaches focused on chemical solutions to more holistic biological ones. This innovation demonstrates the enormous potential of post-harvest technology in Indonesia, not only for improving product quality and safety, but also for creating a more equitable, sustainable, and natural food system that aligns with Indonesia's natural resources (Pratama, 2018).

10.2 Simple Technology for Farmers and MSMEs

The development and adoption of simple technologies is key to increasing the efficiency and added value of horticultural products at the farmer and micro, small, and medium enterprise (MSME) levels. Unlike expensive and complex advanced technologies, this approach focuses on innovations that are easy to implement, affordable, and adaptable to local conditions. The primary goal is to bridge the technology gap, reduce post-harvest losses, and empower farmers to compete in broader markets. These simple technologies often utilize locally available materials and basic post-harvest physiology principles to maintain product quality.

One of the most effective examples of simple technology is evaporation-based storage. For perishable commodities like leafy greens and cut flowers, evaporation can be used to maintain humidity and low temperatures. This method can involve storing them indoors with wet burlap sacks or using earthenware pots placed in containers filled with water. The principle is that the latent heat of evaporation of water absorbs heat from the surrounding air, creating a cooler and more humid environment. This technology requires no electricity and can be built at very low cost.

For drying, many farmers still rely on direct sunlight. While simple, this method is vulnerable to dust, insect contamination, and unpredictable weather. A simple technological innovation that can be implemented is a greenhouse-type solar dryer. This device is made from a wooden or bamboo frame covered with transparent plastic. The trapped solar heat inside increases the temperature and speeds up the drying process, while protecting the product from contamination. This device is particularly effective for drying spices, grains, or herbal products.

Simple packaging also plays a significant role in maintaining post-harvest product quality. Instead of using sophisticated plastic packaging, farmers can use modified packaging made from local materials. For example, packaging made from dried banana leaves, newspaper, or woven bamboo can serve as physical protection. Utilizing post-harvest technologies, such as cold water dipping before packaging, can reduce respiration and transpiration rates, thus helping produce stay fresher longer.

Simple technology focuses not only on storage and drying, but also on sorting and grading. An understanding of post-harvest physiology, such as ideal ripeness, size, and the absence of defects, can be taught to farmers through simple training. To facilitate this, farmers can create simple tools, such as sieves of specific sizes or measuring boards, that help them sort produce based on quality criteria. This process increases the product's selling value by ensuring more uniform quality and meeting market demand.

Transportation and handling equipmentSimple handling is also part of this innovation. Mechanical damage during transport from the field to the collection point is often a significant cause of post-harvest losses. Farmers can use containers or baskets lined with soft materials, such as dry leaves or used sacks, to reduce impact and friction between products. Knowledge of proper product arrangement within the container is also crucial to minimizing damage.

The implementation of this simple technology cannot be achieved without training and mentoring. Farmers and MSMEs must be equipped with adequate knowledge and skills regarding post-harvest physiology, proper handling, and how to use the technology provided. Support from the government, academics, and non-governmental organizations is crucial to ensure effective knowledge transfer and program sustainability. Case studies show that the success of technology adoption depends heavily on how easily it is understood and integrated into daily practices (Wijayanto, 2019).

The development of this simple technology also aligns with sustainability principles. By utilizing local materials, this technology reduces dependence on global supply chains and minimizes the carbon footprint. Furthermore, by reducing post-harvest losses, this technology contributes to the efficient use of natural resources such as water and land. This demonstrates that the most effective solutions are often the simplest and closest to existing resources (Putra, 2021).

Many universities and research institutions in Indonesia have developed and tested these simple technologies. For example, storage techniques using the "Zero Energy Cool Chamber" or "Pot-in-Pot" method have been successfully tested in various regions. The results of this research demonstrate that with minimal investment, farmers and MSMEs can significantly improve the shelf life and quality of their horticultural products.

Ultimately, simple technology for farmers and MSMEs is a concrete manifestation of inclusive and sustainable innovation. The focus is not on creating something new and complex, but on optimizing existing resources and local knowledge. By empowering farmers through accessible and relevant technology, we not only improve food quality and safety but also strengthen the foundations of the rural economy as a whole, as research in the field of agrotechnology confirms (Raharjo, 2020).

10.3 Application of Digital Technology (IoT, Smart Farming) in Post-Harvest

The application of digital technologies such as the Internet of Things (IoT) and smart farming has revolutionized the post-harvest sector, offering precision solutions that were previously unattainable. These innovations enable more accurate monitoring and control of horticultural product storage and distribution conditions, which are directly related to post-harvest physiology. By integrating sensors, software, and connectivity, the supply chain becomes smarter, more transparent, and more efficient, reducing losses and maintaining product quality all the way to the consumer.

One of the key applications of IoT in post-harvest is real-time temperature and humidity monitoring. Wireless sensors placed in storage rooms, transport trucks, or even inside packaging can continuously collect data. This data is then transmitted to a cloud-based platform, accessible by supply chain managers via smartphone or computer. If temperature fluctuations occur that could accelerate respiration and spoilage, the system will send automatic alerts, allowing for immediate corrective action.

In addition to temperature and humidity, sensors can also monitor ethylene and carbon dioxide levels. Ethylene, a ripening hormone, can accelerate the aging of climacteric produce like bananas and mangoes. With ethylene sensors, operators can detect the accumulation of this gas in storage and take measures, such as ventilation, to slow the ripening process. Conversely, CO_2 levelsHigh pressures can be used to control the respiration rate in modified atmosphere (MAP) storage systems, and sensors ensure that gas concentrations remain optimal.

The application of smart farming technology doesn't stop in the field, it continues into the post-harvest stage. Data collected during the growing season, such as watering schedules, fertilization, and pesticide use, can be integrated with post-harvest data. This integration creates a comprehensive traceability system, from seed to consumer. Consumers can scan a product's QR code to view its complete history, providing transparency and building trust (Priyanto & Kusuma, 2021).

Smart sorting and grading systems are also part of digital innovation. Cameras and optical sensors powered by artificial intelligence (AI) can automatically scan produce to detect defects, damage, or ripeness. These systems can separate produce based on established quality criteria with much greater speed and accuracy than human labor. The result is consistent and efficient product classification, which is crucial for meeting stringent market standards and minimizing waste.

The use of digital technology also supports more efficient inventory management. With sensors and digital platforms, the location and condition of each pallet or batch of product can be tracked. This allows the system to automatically manage stock rotation based on the first-in, first-out (FIFO) principle or even based on expiration dates predicted by sensor data. Accurate inventory management reduces the risk of unsold expired products.

Despite its great potential, the implementation of this technology faces challenges, especially in developing countries. High initial investment costs for sensors, software, and connectivity infrastructure pose significant barriers for farmers and MSMEs. Furthermore, digital literacy and adequate technical skills are required to operate and maintain these systems. Therefore, mentoring programs and supportive financing schemes are needed for widespread adoption of this technology.

Digital technology also enables new, more efficient business models. Digital platforms can connect farmers directly with buyers, such as supermarkets or restaurants, eliminating the role of intermediaries. With real-time data on product availability and quality, negotiations can be conducted more transparently. This model not only increases farmers' income but also ensures that delivered products meet agreed specifications (Siregar, 2020).

Ethics and sustainability are also supported by digital technology. With accurate data, food waste can be minimized, a key pillar of sustainability. Furthermore, robust traceability systems ensure responsible practices throughout the supply chain, from pesticide use to working conditions. This technology provides greater accountability and encourages the entire ecosystem to operate more ethically.

Overall, the adoption of digital technologies, such as IoT and smart farming, marks a significant evolution in the post-harvest sector. These technologies provide the ability to monitor and control post-harvest processes with unprecedented precision. By addressing adoption challenges, these innovations have the potential to fundamentally transform the way horticultural products are managed, improving quality and safety, and creating smarter and more efficient supply chains (Susilo, 2019).

10.4 Successful Cases of Postharvest Innovation in Indonesia

Locally-based post-harvest innovation in Indonesia is not merely theoretical, it has been proven successful through various real-life cases, significantly contributing to increasing the added value and competitiveness of horticultural commodities. This case study serves as an important model for understanding how integrating product physiology and technology application can produce practical solutions relevant to social and economic conditions on the ground. This success demonstrates that the adoption of post-harvest technology, regardless of scale, is key to addressing common challenges such as post-harvest losses and price fluctuations.

One notable success story is the development of a mangosteen supply chain for export markets. Mangosteen, dubbed the "queen of tropical fruits," has a skin that is susceptible to physical damage and fungal attack. The innovation implemented involves a strict sorting and grading system based on ripeness and physical quality. Selected fruit is then dipped in a natural fungicide solution or hot water to control pathogens, and packed in specially designed, ventilated containers to minimize damage during transport.

The application of technology to mangosteen doesn't stop there. Disciplined cold chain management, from the orchard to the airport, is an absolute prerequisite. The fruit is cooled immediately after harvest and transported in refrigerated trucks. The use of data loggers to monitor temperatures throughout the journey ensures optimal conditions are maintained. This approach successfully extends the shelf life of mangosteen and ensures the product remains in prime condition upon arrival in distant destinations, such as China and the United Arab Emirates, significantly increasing the selling price.

Another success story can be seen in the local minimally processed vegetable industry. Farmers and MSMEs in the highlands, for example, have successfully processed carrots and green beans into ready-to-cook cut products. Post-harvest innovations include using cold water for washing and cooling, cutting with sharp tools to minimize cell damage, and packaging in vacuum-sealed or simple modified atmosphere plastic bags. This allows vegetables to retain their freshness, color, and high nutritional value.

The key to the success of this innovation lies in the implementation of strict sanitation and hygiene principles. This process relies not only on technology but also on sound quality management, such as hygienic production practices and worker training. This minimally processed product meets the demands of a fast-paced modern lifestyle and adds value to farmers, who previously only sold raw produce at lower prices. This implementation demonstrates that even simple post-harvest technology can create competitive products in the market (Setyaningsih, 2020).

Innovation is also evident in the utilization of agro-industrial waste. A company in East Java, for example, has successfully converted coffee husk waste from the dry milling process into liquid and solid organic fertilizer. This innovation is based on an understanding of the high nutrient content of this waste, which was previously discarded and polluted the environment. The technology used is relatively simple, involving a controlled fermentation process with the help of local microorganisms. This organic fertilizer not only provides new economic value but also supports sustainable agricultural practices and reduces the environmental footprint.

Another successful case involves utilizing browning in tropical fruit peels, previously considered a defect. A startup in Bali has successfully transformed brown mangosteen peels into an antioxidant-rich powder used as a raw material for supplements and cosmetics. This innovation required in-depth research into the bioactive compounds in the peel and the appropriate drying technology to preserve them. This demonstrates that understanding post-harvest physiology and chemistry can transform the perspective of "waste" into "treasure" (Prasetyo & Budiarti, 2019).

A key factor behind the success of these cases is strong collaboration between various parties. Farmers, university academics, local governments, and industry players work together to identify problems, develop solutions, and facilitate technology adoption. University involvement, for example, is often a valuable source of knowledge and technical guidance for farmers and MSMEs. Without this synergy, innovations developed would remain in the laboratory and unable to be implemented in the field.

Technology adoption in these cases also demonstrates the ability to adapt to local contexts. The solutions chosen are not always the most expensive or sophisticated, but rather the ones best suited to available resources and infrastructure. This reflects the understanding that the sustainability of innovation is determined not only by its technical effectiveness but also by the economic and social capacity of the community to adopt and maintain it (Wijayanti, 2018).

Overall, these successful case studies of post-harvest innovation in Indonesia provide concrete evidence that investments in knowledge and technology can produce transformative change. They demonstrate that with a proper understanding of commodity physiology and the application of relevant technologies, both simple and sophisticated, Indonesian horticultural products can achieve higher quality standards, reduce losses, and compete effectively in global markets. These cases serve as inspiration and a roadmap for future agricultural sector development.

CHAPTER 11
OBE-Based Learning and Assessment Strategies

The modern educational paradigm has shifted from a traditional content-focused approach to a results-oriented model or Outcome-Based Education (OBE), where the primary emphasis is on what students can do after completing a course. This chapter will outline learning and assessment strategies designed to integrate OBE principles into the Postharvest Physiology and Technology course, beginning with an exploration of innovative learning methods such as Problem-Based Learning (PBL), Project-Based Learning (PjBL), and Case Studies that encourage students to think critically and solve real-world problems. Next, we will discuss how to develop a clear and structured OBE-based Semester Learning Plan (RPS), and how to measure learning outcomes through a comprehensive rubric-based assessment, covering aspects of knowledge, skills, and attitudes. Finally, this chapter will present an example of a project rubric specific to postharvest innovation as a practical guide to ensure an objective, transparent, and measurable assessment process.

11.1 Learning Methods: PBL, Project-Based Learning, Case Study

A results-oriented learning approach, or Outcome-Based Education (OBE), demands a shift from traditional lecture methods to more interactive, student-centered strategies. In the context of postharvest physiology and technology courses, this means students must not only memorize theory but also apply their knowledge to solve real-world problems. Therefore, the application of methods such as Problem-Based Learning (PBL), Project-Based Learning (PjBL), and Case Studies is highly relevant. These three methods are designed to develop critical, analytical, and collaborative skills essential for professionals in this field.

One effective method is Problem-Based Learning (PBL). In PBL, students are confronted with complex and unstructured post-harvest problems, such as "Why do mangoes harvested from orchard A rot more quickly than those from orchard B, even though they are harvested at the same level of ripeness?" Students then independently identify any gaps in their knowledge, gather information from various sources, and work in groups to formulate logical solutions. This process encourages students to think holistically, integrating physiological principles with environmental and technological factors.

PBL applications in postharvest courses can be implemented by providing short case studies or data-driven scenarios. For example, students might be given temperature and humidity data during storage, as well as product condition reports, and asked to diagnose the cause of damage. This approach trains students to think like consultants or quality managers, analyzing data, generating hypotheses, and proposing corrective actions. In this way, they not only learn theory but also master problem-solving skills, which are highly sought after in the industry.

While PBL focuses on problem-solving, Project-Based Learning (PjBL) challenges students to develop tangible products or solutions. In the post-harvest context, projects might include designing a simple storage system for local farmers, developing minimally processed products for a specific commodity, or creating a prototype for a computer vision-based fruit sorting tool. These projects typically involve several stages, from planning and implementation to presentation of the final results. PjBL effectively bridges the gap between theory and practice.

One example of PjBL implementation is the "Natural Preservative Innovation" project. Students were asked to identify local natural ingredients (e.g., guava leaf extract) and test their effectiveness in extending the shelf life of certain fruits. They had to design experiments, collect physiological data such as respiration rate and weight loss, analyze the results, and present them in technical reports and presentations. This project not only trained technical skills but also project management, communication, and teamwork (Fadilah & Hidayat, 2021).

Another highly relevant method is the case study. Unlike problem-focused PBL, a case study analyzes a real-life case, whether a success or failure. Students are asked to review the details of the case, analyze the factors that influenced the outcome, and identify lessons learned. For example, analyzing a case of failed vegetable exports due to pesticide residue contamination would prompt discussion about the importance of quality standards, international regulations, and traceability.

Case studies can also be used to highlight the success of local innovations. Students can analyze the success story of an MSME that successfully processed fruit waste into value-added products. This analysis will include factors such as the technology used, marketing strategies, and economic impact on the local community. Thus, case studies not only hone analytical skills but also provide inspiration and a deeper understanding of the dynamics of the industry as a whole.

The synergistic integration of these three methods within a single course creates a rich learning experience. PBL can be used at the beginning of the semester to introduce basic concepts through simple problem-solving. Case studies can be used mid-semester to analyze real-world applications, and PjBL can serve as a culmination of learning at the end of the semester, where students apply all the knowledge and skills they have acquired to complete a comprehensive project (Sari & Wijaya, 2019).

Implementing these methods requires support from lecturers as facilitators, not just as providers of material. Lecturers must be able to design relevant problems and projects, provide constructive feedback, and guide students through the independent learning process. Furthermore, the curriculum must be designed flexibly to accommodate the time needed for group exploration and collaboration.

Ultimately, the OBE-based learning method in postharvest physiology and technology courses will produce graduates who not only master theory but also possess the soft and hard skills required by industry. They will be prepared to become innovators, problem solvers, and leaders in the agricultural sector, thereby making a real contribution to improving the quality and competitiveness of Indonesian horticultural products (Kusumo, 2020).

11.2 OBE-Based Semester Learning Plan (RPS)

The curriculum shift towards Outcome-Based Education (OBE) positions the Semester Learning Plan (RPS) as a strategic document that is no longer simply a list of topics, but rather an integrated roadmap for achieving predetermined learning outcomes. In the post-harvest physiology and technology course, the OBE-based RPS serves as a comprehensive guide, systematically linking graduate competencies, course learning outcomes, teaching materials, learning methods, and assessment systems. Thus, the RPS becomes a key tool for lecturers to design relevant and measurable learning experiences, ensuring that each activity contributes to the achievement of the expected outcomes.

Developing an OBE-based RPS begins with identifying course learning outcomes (CPMK) that specifically support the graduate learning outcomes (CPL) of the study program. The CPMK should be formulated in a measurable form, describing what students should know and be able to do after completing the course. For example, instead of simply writing "understand postharvest physiology," a more measurable CPMK might read "analyze physiological factors affecting the shelf life of tropical fruits." This clear formulation will serve as the foundation for all subsequent RPS components.

Once the CPMKs have been established, the next step is to map them to the learning materials. Instead of presenting the materials separately, they are grouped into topics that support the achievement of the CPMKs. For example, a CPMK focused on "analyzing post-harvest damage" would be supported by materials on respiration rate, transpiration, enzymatic browning, and microbial contamination. This mapping ensures that each topic taught has a clear objective and is relevant to the targeted outcomes.

Next, the RPS must detail the learning methods that will be used to facilitate the achievement of the CPMK. In the context of OBE, learning methods should be active and student-centered. The RPS may outline the use of Problem-Based Learning (PBL) to encourage problem-solving, Project-Based Learning (PjBL) to develop innovation prototypes, or case studies to analyze real-world cases. Each method should be explicitly linked to a specific CPMK, demonstrating how the activity will help students achieve the desired outcomes.

A crucial part of an OBE-based RPS is the assessment system. Assessments should be designed to measure CPMK achievement, not simply test memory. Therefore, the RPS should explain the types of assessments used, such as formative tests, project assignments, presentations, and comprehensive exams. The weight of each assessment should be proportional to its contribution to CPMK achievement, so students understand the importance of each assignment.

The use of assessment rubrics is a vital element of an OBE-based RPS. Rubrics provide clear and transparent criteria for assessing student performance, not only in terms of knowledge but also skills and attitudes. The RPS should include or reference the rubric used for each assignment so students know what is expected of them. For example, a rubric for a post-harvest innovation project might assess technical (technological effectiveness), analytical (data analysis), and collaborative (teamwork) aspects.

The lesson plan (RPS) planning must also consider a progressive learning flow. Material and assignments should be structured in such a way that their difficulty and complexity increase as the semester progresses. The initial phase might focus on understanding basic concepts, while by the end of the semester, students are expected to be able to integrate these concepts to complete more complex projects. This progression ensures that students build their competencies gradually and systematically.

Developing an OBE-based RPS requires close coordination and collaboration between course instructors. Regular review and evaluation of the RPS is also crucial to ensure its relevance and effectiveness. Lecturers must be open to feedback from students and industry to continuously refine the RPS, ensuring the course remains relevant to job market needs (Santosa, 2021).

The OBE-based RPS must also be accessible and understandable to students. This document should serve as a clear learning contract, in which students understand the goals, expectations, and how they will be assessed. In this way, the RPS empowers students to take ownership of their learning and be accountable for achieving agreed-upon outcomes. This transparency builds trust and creates a positive learning environment.

Ultimately, the OBE-based RPS for postharvest physiology and technology courses represents a commitment to relevant and future-oriented education. This document ensures that graduates possess not only theoretical knowledge but also the practical competencies and professional attitudes needed for a career in the agricultural industry (Hadi & Suryani, 2019). With a well-designed RPS, this course will effectively contribute to the development of human resources ready to face global challenges (Putra, 2018).

11.3 Rubric-Based Assessment (Knowledge, Skills, Attitudes)

Assessment within the Outcome-Based Education (OBE) framework is more than just measuring knowledge, it is designed to evaluate the achievement of learning outcomes encompassing knowledge, skills, and attitudes. To ensure objective, transparent, and measurable assessment, rubric-based assessment is used. A rubric is a tool that contains clear assessment criteria for each level of performance, providing explicit guidance to students on the expectations they should achieve. In postharvest physiology and technology courses, this rubric is a vital instrument for measuring holistic competency.

Rubrics break assessment down into three main dimensions: knowledge, skills, and attitudes. Knowledge is evaluated through criteria that measure the depth and breadth of a student's conceptual understanding. For example, in a rubric for a project report, knowledge criteria might include "accuracy in explaining the principles of postharvest physiology" or "understanding of the role of temperature and humidity in product storage." These assessments measure not only recall but also the ability to apply these concepts in relevant contexts.

The second dimension, skills, focuses on a student's ability to perform a task or apply a procedure. In a rubric, these criteria might include "ability to design post-harvest experiments," "ability to operate laboratory equipment," or "ability to analyze product damage data." Skills assessment can be conducted through direct observation, project product evaluation, or demonstration. The rubric provides a clear scale, for example, from "not competent" to "highly competent," for each skill being assessed.

Attitude is often the most difficult component to assess, yet it is crucial in OBE. Attitude encompasses attributes such as professional ethics, teamwork, initiative, and responsibility. In a rubric, attitude criteria might include "active participation in group discussions," "demonstrates initiative in problem-solving," or "maintains the integrity of experimental data." Attitude assessment can be conducted through instructor observation, peer assessment, or reflective journaling. This rubric-based assessment provides a systematic framework for evaluating students' attitude development throughout the semester.

The primary benefits of rubric-based grading are objectivity and transparency. With pre-established criteria, both instructors and students have a shared understanding of what is expected. This reduces bias in grading and allows students to proactively improve their performance. Rubrics also facilitate more specific and detailed feedback. Rather than simply assigning a score, instructors can highlight students' areas of strength and weakness based on the criteria outlined in the rubric.

Rubrics can be designed for various types of assignments and assessments, from lab reports and presentations to comprehensive final projects. For example, a lab report rubric might have specific criteria for writing format, data analysis, and conclusions. Meanwhile, a presentation rubric might assess oral communication, data visualization, and responses to questions. This flexibility allows instructors to design assessments tailored to the characteristics of each CPMK.

The use of rubrics also empowers students to conduct self-assessment. By comparing their performance against the criteria in the rubric, students can identify areas for improvement. This skill is crucial for lifelong learning. Furthermore, rubrics facilitate peer assessment, where students can provide feedback to their group mates based on objective criteria.

Designing an effective rubric requires time and careful thought. The formulated criteria must be relevant to the learning outcomes, and the performance descriptions for each level must be clear and observable. Having examples of successful rubrics from other study programs or universities can provide valuable references. Discussions with fellow faculty can also help refine the rubric to make it more valid and reliable.

Rubric-based assessment benefits not only students but also lecturers. Rubrics simplify the assessment process, especially for complex assignments. Lecturers can provide consistent scores and feedback, even for large numbers of students. Furthermore, data from rubrics can be used to analyze overall learning outcomes, helping lecturers and study programs identify areas of the curriculum that need improvement (Suhartini & Wahyudi, 2021).

In short, rubric-based assessment is an essential tool in the OBE education ecosystem. In postharvest physiology and technology courses, rubrics ensure that assessments measure not only theory but also students' ability to apply their knowledge, develop practical skills, and demonstrate professional attitudes relevant to industry (Purnomo, 2019). The integration of rubrics into every aspect of learning demonstrates a commitment to producing graduates who are not only intelligent but also competent and have character (Wibowo, 2020).

11.4 Post-Harvest Innovation Project Rubric Example

Project Title 1:

Post-Harvest Technology Innovation to Improve the Quality and Shelf Life of Local Fruit

Project Description:

Students are asked to design a simple post-harvest technology innovation that can be applied to local fruit or vegetable commodities. The project includes analyzing quality and yield loss issues, designing the technology innovation, conducting trials or simulations, and presenting the results in a written report and demonstration.

Table 1. Post-Harvest Innovation Project Assessment Rubric

Rated aspect	Assessment criteria	Score 1	Score 2	Score 3	Score 4
Post-Harvest Problem Identification (20%)	Students' ability to identify real problems in post-harvest commodities (examples: mechanical damage, weight loss, browning)	The problem is unclear and irrelevant	The problem is quite relevant but the description is very general.	The problem is relevant and supported by simple data.	The problem is very clear, relevant, and supported by literature/field data
Creativity and Innovation (25%)	The level of novelty, originality, and usefulness of the innovation idea	Innovation is copying without modification	Innovation exists but is very simple	Innovation is creative and relevant enough to be applied	The innovation is very creative, applicable, and has the potential to be developed further.
Application of Postharvest Scientific Concepts (20%)	Accuracy in connecting post-harvest physiology and technology concepts with innovation	There is no scientific basis	There is a scientific basis but it is not consistent.	The scientific concept is quite precise and supports innovation.	The scientific concept is very precise, comprehensive, and consistently supports innovation.
Project Methodology	Whether the design of the	There is no methodology	The methodolog	The methodolo	The methodology is

Rated aspect	Assessment criteria	Score 1	Score 2	Score 3	Score 4
and Design (15%)	method/experiment/simulation is systematic or not		y exists but is unclear.	gy is quite clear, testable	very clear, systematic and replicable.
Presentations and Reports (10%)	Quality of scientific communication both oral and written	Reports and presentations are not coherent	The report is quite coherent, the presentation is not clear enough.	The report is clear, the presentation is quite communicative.	The report is very systematic, the presentation is convincing and communicative.
Teamwork and Attitude (10%)	Collaboration, responsibility, and academic ethics	No cooperation, bad attitude	There is cooperation but there is less balance	Cooperation is quite good, responsibility is maintained	The cooperation is very solid, ethical and full of responsibility.

Final Score:

- 85 – 100 = Very Good
- 70 – 84 = Good
- 55 – 69 = Enough
- < 55 = Less

Explanation

This rubric is designed based on Outcome-Based Education (OBE) so that every aspect of the assessment is directly linked to learning outcomes. Identification of post-harvest problems trains students to think critically according to analytical learning outcomes, creativity and innovation measurement higher order thinking skills (HOTS), the application of scientific concepts tests mastery knowledge and application, project methodology trains skills problem solving, presentations and reports sharpen communication skills, and teamwork assessments of skills and academic ethics. Thus, this rubric measures not only the final project outcome but also the learning process, in accordance with the OBE principle, which focuses on achieving real competencies relevant to the workplace.

Project Title 2:
Application of Edible Coating Modified Cassava Starch-Based Formulation to Extend the Shelf Life of Local Mangoes
Project Description:
Students design technological innovations in the form of edible coating made from modified cassava starch with pandan leaf extract as a natural antioxidant. The goal is to slow the respiration rate and prevent browning in local mangoes, thus extending their shelf life when distributed to modern markets. This project is carried out in the following steps:

1. Identification of post-harvest mango quality problems (quickly ripening, quick to rot).
2. Literature study on*edible coating*experience.
3. Making a simple coating solution from cassava starch + pandan extract.
4. Application on physiologically ripe mangoes.
5. Simulation of storage for 7 days at room temperature, observed changes in color, hardness, and level of damage.
6. Preparation of innovation reports and presentation of results.

Table 2. Assessment with Rubric

Rated aspect	Description of Student Results	Score
Post-Harvest Problem Identification(20%)	Students are able to explain that local mangoes spoil quickly due to high respiration rates, with literature data showing weight loss of 15–20% after 5 days at room temperature.	4
Creativity and Innovation(25%)	Using local cassava starch as an affordable and environmentally friendly ingredient and pandan extract as a natural antioxidant, this innovation combines local potential with simple technology.	4
Application of Postharvest Scientific Concepts(20%)	Students explained that edible coatings form a semi-permeable layer that reduces transpiration, slows respiration, and delays ripening. Postharvest physiology concepts were consistently applied.	4
Project	The methodology is clear, from material preparation, coating, storage, to	3

Rated aspect	Description of Student Results	Score
Methodology and Design(15%)	quality evaluation (color, texture, damage). However, measurements are still simple (visual, manual) without instruments.	
Presentations and Reports(10%)	The written report is neat and structured, the presentation uses communicative visual media, students are able to answer questions well.	4
Teamwork and Attitude(10%)	Each team member has a role, collaboration is seen in the division of tasks, as well as ethical attitudes during presentations.	4

Total Score = (4×20) + (4×25) + (4×20) + (3×15) + (4×10) + (4×10) = 80 + 100 + 80 + 45 + 40 + 40 = 385 / 5 = 77

Category: Good (70–84)

Conclusion

This project demonstrated that students were able to identify real-world problems in mango post-harvest management, propose solutions based on local resources, and connect innovations to post-harvest physiology theory. Although the methodology was simple, the resulting innovations were quite applicable and have the potential for further development.

CHAPTER 12
Post-Harvest Project and Practice (OBE Project)

Effective learning in postharvest physiology and technology requires students to not only understand the theory but also be able to apply it practically through real-world projects. This chapter will present a series of postharvest projects and labs specifically designed according to the Outcome-Based Education (OBE) approach, ensuring students develop industry-relevant competencies. These projects cover a broad spectrum of postharvest issues, from analyzing climacteric fruit respiration to simulating complex horticultural cold chains. Each project will be accompanied by a detailed OBE-based assessment rubric, providing clear guidance for evaluating students' knowledge, skills, and attitudes, ensuring each activity contributes directly to the achievement of the established learning outcomes.

12.1 Project 1: Analysis of Climacteric Fruit Respiration

Short description

Students analyzed the respiration patterns of climacteric fruit to identify the occurrence of the climacteric peak and its implications for post-harvest handling strategies. Ambon bananas or physiologically ripe tomatoes were suggested as commodities because they are readily available and exhibit clear respiration peaks. Measurements were conducted using a closed-system method using a CO2 gas sensor, followed by calculation of respiration rate based on fruit mass and time interval, mapping of respiration curve against storage time, interpretation of pre-climacteric, peak, and decline phases, as well as recommendations for relevant technological interventions such as storage temperature, atmospheric modification, and application of ethylene inhibitors.

Targeted OBE Learning Outcomes

Students are able to explain the basic physiology of climacteric fruit respiration and its relationship to ethylene, design and conduct simple experiments to measure respiration rates, analyze and visualize data to identify the climacteric peak, and formulate applicable and evidence-based post-harvest handling recommendations. In addition, students demonstrate scientific communication skills, team collaboration, and academic ethics.

Materials and equipment

Homogeneous climacteric fruit based on size and ripeness, suitable sized sealed jars that allow for adequate headspace ratio, digital scales, storage thermometer and hygrometer, CO_2 meter first option CO sensor portable in ppm units, the second option is the CO absorption system with 1 N NaOH solution and standard HCl back titration with phenolphthalein indicator, time recorder, gloves and basic PPE, data worksheet, spreadsheet software.

Core design and procedures

The samples were weighed and initial visual characteristics were recorded, each replication was placed in a closed container with a known headspace volume and equipped with a gas sampling port, the storage room temperature was maintained and recorded. For the CO sensor, CO concentration measured at the start of closure and after a fixed interval e.g. 30 to 60 minutes to obtain the increase in CO, the respiration rate is calculated as milligrams of CO per kilogram per hour based on changes in concentration, headspace volume, fruit mass, and incubation time. For the titration method, the container is given a cup containing NaOH which absorbs CO for a fixed interval, then the remaining NaOH is titrated to determine the amount of CO absorbed and converted to respiration rate, measurements were repeated daily for at least five days to capture the rising, peak, and falling phases. The data were plotted as a curve of respiration rate versus storage days, peak points were identified, and temperature and humidity were listed as covariates.

Data processing and analysis

The concentration calculation is converted to CO mass using the simple ideal gas law or conversion factor from ppm to mg per liter, then normalizing by fruit mass and time to produce units of mg CO per kilogram per hour, the mean and standard deviation between replicates were calculated, the respiration curve was presented with a trend line and simple confidence interval, the climacteric phase was characterized qualitatively based on the gradient changes, the relationship between storage temperature and peak magnitude was discussed, and, if available, Q was estimated.$_{10}$based on two different storage temperatures to illustrate the sensitivity of respiration to temperature.

Expected output

A concise scientific report containing the scientific background and working hypothesis on the occurrence of respiratory peaks in selected commodities, detailed methodology including respiration rate calculations, results in tables and graphs with descriptive statistical analysis, a discussion linking the findings to the theory of climacteric physiology and the role of ethylene, technical recommendations for specific and feasible post-harvest handling for small scale, and a short oral presentation visualizing the respiration curves and their implications for quality and shelf life.

Data safety and quality

Students apply PPE, handle standard bases and acids safely, prevent container leaks that cause reading bias, perform simple calibration of CO sensors or titrant standardization, running replications at least three times, and maintaining data traceability through log books and calculation attachments.

Table 3. Assessment Rubric for the Climacteric Fruit Respiration Analysis (OBE) Project

Aspects and Weight	Level 1	Level 2	Level 3	Level 4
Problem formulation and scientific basis, 5%	The problem is unclear, the theory is irrelevant.	General problems, partial theories	Clear problem, adequate theory	Very specific problems, comprehensive and current theories
Experimental design and method traceability, 20%	Inadequate design, undocumented steps	Decent design but weak controls or minimal documentation	Systematic design with basic controls and sufficient documentation	Very systematic design, adequate control, neat and replicable SOPs
Data acquisition and quality control, 15%	Little data, no replication, lots of data loss	Limited replication, there are inconsistencies	Adequate replication, data consistent with baseline QC records	Strong replication, complete QC records, proven calibration or standardization
Calculation and visualization, 15%	Wrong calculations, uninformative graphs	Partially correct calculations, simple graph	Calculations are correct, graphs are clearly labeled.	Accurate calculations with unit propagation, professional graphs with uncertainty
Biological interpretation of the climacteric peak, 20%	Does not identify phase or peak	Identifying peaks but weak reasoning	Identify and explain phases with scientific arguments	In-depth interpretation linking ethylene, temperature, and physiological implications
Post-harvest handling recommendations, 10%	Unrealistic recommendations	General recommendations without parameters	Specific recommendations with basic parameters	Evidence-based, applicable recommendations with quality and cost impact estimates

Aspects and Weight	Level 1	Level 2	Level 3	Level 4
Scientific communication, 10%	Chaotic structure, no citations	Adequate structure, language is less precise	Good structure, adequate citations	Very good structure, precise language, very strong visuals and citations.
Collaboration, ethics, and professionalism, 5%	Unclear team roles, ethical violations	Unbalanced roles, minimum ethical compliance	Roles are clear, ethics are adhered to	Effective collaboration, exemplary leadership and ethics

Final score: obtained from the sum of the weights of each aspect at levels 1 to 4 which are mapped to a score of 1 to 4, then converted to a percentage. Recommended value mapping, 85 to 100 is very good, 70 to 84 is good, 55 to 69 is sufficient, below 55 requires improvement.

OBE alignment explanation

The problem formulation and scientific basis aspects map the achievement of knowledge and understanding of core respiration concepts, experimental design, data acquisition, calculation, and visualization focus on science process skills and problem solving, interpretation of climacteric peaks and treatment recommendations assess the ability to apply and make contextual decisions relevant to industry, scientific communication evaluates oral and written scientific literacy, while collaboration and ethics reflect professional attitudes and responsibilities. Thus, the rubric assesses not only the final product in the form of a respiration graph, but also the scientific process, analytical accuracy, and practical relevance that are the essence of output-based learning.

Datasheet and calculation templates

Sample identity includes variety, maturity level, mass, temperature and humidity of the storage room, headspace volume is recorded, the start and end times of incubation per replication are written, CO readings are recorded.The start and end values are recorded or the normality of the titrant is listed for the titration method, the calculation of the respiration rate is expressed in units of mg COper kilogram per hour, statistical summary including mean, standard deviation, and number of replicates, quality control records containing calibration dates, blank tests, and leak records, a graph of respiration rate against storage days with annotations of pre-climacteric, peak, and post-peak phases to facilitate interpretation.

Minimum passing criteria

Respiration curves that show logical and accountable trends, determination of the climacteric peak based on measured data rather than assumptions, a set of realistic and parameterized handling recommendations such as storage temperature, ventilation, or the use of ethylene absorbers, as well as reports and presentations that meet the standards of scientific communication and academic integrity.

12.2 Project 2: Effect of Storage Temperature on the Quality of Leafy Vegetables

Short description

Students assess the effects of various storage temperatures on the quality of leafy vegetables (e.g., lettuce or spinach) with the aim of determining the optimal temperature range for extending shelf life while maintaining sensory and nutritional quality. The project includes designing comparative experiments at a minimum of three temperature treatments (e.g., 4°C, 10°C, and 20°C), measuring quality parameters such as weight loss, firmness/texture, color (Lab* if available or visual score), chlorophyll content or simple indicators of nutrient degradation (e.g., vitamin C content or extract color test), and simple surface microbial assessment if facilities permit. Observations are made daily or every 2 days for an appropriate period (e.g., 7–14 days) to compare the rate of quality decline and calculate a practical shelf life based on a defined quality threshold.

Targeted OBE Learning Outcomes

Students are able to design and carry out controlled experiments to test post-harvest environmental factors, collect and analyze quantitative and qualitative data, interpret the relationship between temperature and physiological quality parameters, develop applicable post-harvest handling recommendations, and demonstrate good scientific communication and professional teamwork.

Materials and equipment

homogeneous leaf vegetables (uniform sample units), digital weighing sheets, microbalance for substrate if necessary, weighing sheets for initial and periodic weights, absorbent cloth or paper, ventilation containers or trays for each treatment, thermometer and hygrometer for each room/treatment, controlled temperature storage (refrigerator/incubator/cooling chamber) at 4°C, 10°C, 20°C, simple texture tester (measured manual pressure or standardized sensory assessment), spectrophotometer or vitamin C kit if available, gloves, sterilization materials, data worksheet, spreadsheet software.

Core design and procedures

A. Select a variety and collect a homogeneous sample, wash if appropriate, drain, and weigh for initial weight.
B. Divide the samples into replicate groups with a minimum of three replicates per temperature treatment. Record the initial conditions (color, texture, weight).
C. Place each replicate on a different shelf or tray in the storage unit at the specified temperature, recording the temperature and RH periodically.

D. Periodic observations: measure weight loss (%), visual score of damage (e.g. 0–5), hardness/texture if available, color L*a*b* or color assessment, and if possible, a vitamin C or crude chlorophyll test. If available, perform a surface microbial test (plate count) on the first and last day.
E. Determine quality thresholds (e.g. weight loss > 10%, damage score > 3, or vitamin C loss > 30%) for shelf life estimation.
F. Document all data, photograph samples for each observation, and note anomalies.

Data processing and analysis

Calculate relative weight loss, plot quality parameters versus storage days for each temperature, calculate the rate of quality decline (e.g., percent per day), use simple statistical tests (one-way ANOVA or nonparametric tests if n is small) to compare treatments, determine practical shelf life based on quality threshold criteria, discuss physiological mechanisms (respiration, transpiration, membrane changes) that explain differences between temperatures, and analyze experimental limitations and scale-up recommendations.

Expected output

A scientific report containing theoretical background, complete methodology, tables and graphs of results, statistical analysis, physiological interpretation, temperature recommendations and post-harvest practices for the tested leafy vegetables, and an oral/poster presentation presenting the main findings.

Data safety and quality

Laboratory hygiene and sanitation practices during vegetable handling, use of PPE, handling of simple chemicals according to procedures, calibration of scales and measuring instruments, replication of at least three times, complete documentation including photos, and management of organic waste.

Table 4. Project Assessment Rubric: Effect of Storage Temperature on Leaf Vegetable Quality (OBE)

Aspects and Weight	Level 1 (1)	Level 2 (2)	Level 3 (3)	Level 4 (4)
Formulation of objectives and literature review, 10%	Vague objectives, minimal or irrelevant literature	Objectives exist but are general, literature review is limited	Specific objectives, sufficient and relevant literature	The objectives are very specific, the literature review is comprehensive and contextual
Experimental design and treatment control, 20%	Inadequate treatment, lack of replication, poor control	Basic design exists but control or replication is weak	Good design, adequate replication and clear controls	Excellent design, strong treatment rationalization, perfect replication and control
Field/lab implementation and documentation, 15%	Implementation is chaotic, data is missing, documentation is poor.	Implementation is adequate but there are documentation gaps	Neat implementation, adequate documentation (photos, logs)	Meticulous execution, complete and organized documentation
Acquisition of quality data (weight, color, texture, nutrition), 15%	Minimum or invalid measurement	Measurements exist but the methodology is less precise	Valid and consistent measurement	Highly valid measurement, complete and validated quantitative method
Statistical analysis and visualization, 15%	No analysis or wrong analysis	Basic analysis without significance test	Statistical analysis is correct, graphs are clear	Accurate statistical analysis with interpretation, informative graphs showing uncertainty
Physiological interpretation and post-harvest implications, 15%	Superficial or erroneous interpretation	Interpretation exists but lacks depth	Good interpretation, linking basic physiological mechanisms	In-depth interpretation, linking mechanisms, operational implications and cost/risk recommendations
Scientific communication (reports & presentations), 5%	The report is not well organized, the presentation is not communicative	Report is adequate, presentation is average	Good report, clear and structured presentation	Very professional report, persuasive presentation with quality visuals

Aspects and Weight	Level 1 (1)	Level 2 (2)	Level 3 (3)	Level 4 (4)
Teamwork, ethics, and time management, 5%	Poor collaboration, ethical violations, late	Teamwork has a small problem, ethics are ok	Good teamwork, ethics maintained, deadlines met	Exemplary teamwork, leadership, exemplary ethics, all deadlines met

How to calculate the score: For each aspect, assign levels 1–4 according to performance. Multiply the level score by the aspect weight and then add all the results to get the final percentage score. A quick calculation example: if a student gets level 3 for all aspects, the score = (10%×3/4 + 20%×3/4) is converted to the final percentage. The final score mapping: 85–100 is very good, 70–84 is good, 55–69 is sufficient, <55 is poor.

OBE alignment explanation

This rubric links each aspect of the assessment to learning outcomes: formulation and literature review map conceptual understanding, experimental design, implementation, and data acquisition assess practical skills and scientific reasoning, statistical analysis and visualization assess quantitative skills and data literacy, physiological interpretation and post-harvest recommendations assess the application of knowledge to real-world contexts, scientific communication and teamwork assess professional skills and attitudes. Weighting is designed to emphasize experimental and analytical skills (50% total) in line with the OBE-based practicum's objective of assessing real-world skills applicable in the field or industry.

Recommended data sheet short template

A. Identity: variety, origin, harvest date, pre-handling conditions.
B. Treatment: temperature (°C), RH (%), replication.
C. Observations per day: date, day, weight (g), % weight loss, visual damage score (0–5), texture value, color value (L ab or score),

nutritional test results (mg/100 g vitamin C), microbial records if any (CFU/cm²).

D. Temperature/RH log: record of calibrations and anomalies.
E. Labeled documentation photos.
F. Statistical summary: mean, SD, n, significant test results.

Minimum project passing criteria

A. A logical experimental design with a minimum of three temperature treatments and three replications.
B. Complete dataset for key parameters (weights and minimum visual scores), quality versus time graph showing differences between treatments.
C. Interpretations linking quality changes to basic physiological mechanisms and realistic storage temperature recommendations.
D. Structured written reports and short presentations, as well as field documentation evidence.

12.3 Project 3: Application of Natural Edible Coating on Local Fruits

Short Description

Students carry out the application edible coating natural ingredients to extend the shelf life of local fruits (e.g., mango, guava, or banana). This project aims to evaluate the effectiveness of natural coatings based on starch, chitosan, or pectin with the addition of plant extracts as antibacterials or antioxidants on the rate of fruit quality decline during storage. Parameters observed include weight loss, fruit flesh firmness, skin color changes, the level of surface microbial attack, and simple consumer preferences (limited sensory testing). The project emphasizes the integration of postharvest physiology concepts with environmentally friendly technological innovations.

Targeted OBE Learning Outcomes

Students are able to:

A. Explain the physiological principles of fruit damage due to respiration, transpiration, and microbes.
B. Designing and implementing application experiments edible coating on local fruit.
C. Collect, analyze, and present fruit quality data systematically.
D. Interpreting the effectiveness of coatings in slowing down deterioration based on scientific mechanisms.
E. Communicating research results in the form of scientific reports and presentations.
F. Demonstrate collaborative, creative and ethical attitudes in teamwork.

Materials and Equipment

Homogeneous local fruit (e.g. physiologically ripe mango), coating materials (cassava starch, chitosan, or pectin, aromatic spice/leaf extract), solvent and heating tools, digital scales, beakers, soaking containers, storage trays, refrigerators/room temperature chambers, thermometers and hygrometers, analytical scales for weight, color assessment (visual scale or colorimeter if available), simple texture measuring tools (manual pressure test/sensory assessment), and observation worksheets.

Core Design and Procedures

A. Prepare a natural coating solution (e.g. 3% cassava starch with pandan leaf extract).
B. Divide local fruit into two groups: control (uncoated) and treatment (coated). If possible, use more than one formula variation.
C. Apply the coating by dipping or spraying, dry at room temperature.

D. Store the fruit at room temperature or low temperature, observe changes every 2 days until the fruit spoils.
E. Record weight loss (%), skin color, flesh firmness, level of surface microbial contamination (visual observation of mold), as well as limited sensory testing for visual preference.
F. Compare the differences between the control and treatment based on numerical and graphical data.

Data Processing and Analysis

The data was compiled into a table, the mean and standard deviation were calculated, and then a graph of quality development versus time was created. Coating effectiveness was assessed based on significant differences (lower weight loss, slower color change, and less damage) compared to the control. The results were analyzed physiologically. edible coating forms a semi-permeable layer that reduces respiration, transpiration, and microbial growth.

Expected Output

A. Scientific reports contain theoretical background, methodology, results (tables, graphs, photos), discussion, conclusions, and recommendations.
B. Group presentations that visualize the results and demonstrate potential applications in the field.
C. An innovative product in the form of a simple coating formula that can be applied practically.

Table 5. Assessment Rubric for the Edible Coating Application Project on Local Fruit (OBE)

Aspects and Weight	Level 1 (1)	Level 2 (2)	Level 3 (3)	Level 4 (4)
Problem formulation & scientific basis (10%)	The problem is unclear, the theory is irrelevant.	General problems, minimal theory	Clear problem, relevant theory	Specific issues, comprehensive & cutting-edge theories
Innovation &	Just copy, no	There is a	Creative formula	Very innovative,

Aspects and Weight	Level 1 (1)	Level 2 (2)	Level 3 (3)	Level 4 (4)
creativity formula (15%)	modification	simple modification	with additional local ingredients	applicable formula, has the potential to be developed
Experimental design & methodology (20%)	Unsystematic, without control	There is control but replication is limited	Clear methodology, sufficient control & replication	The methodology is highly systematic, fully replicable, replicable
Data acquisition & documentation quality (15%)	Minimal/inconsistent data	Data exists but is incomplete	Data is consistent, photo documentation is sufficient	The data is very complete, consistent, the documentation is neat & clear
Analysis & visualization of results (15%)	No analysis, unclear graphs	Shallow analysis, simple charts	Correct analysis, clear & informative graphs	In-depth analysis, professional charts with strong interpretation
Physiological interpretation & practical implications (15%)	Common/wrong interpretations	Interpretation exists but is shallow	Good interpretation, related to the post-harvest concept	Very in-depth interpretation, linked to scientific concepts & field applications
Scientific communication (5%)	Reports & presentations are not coherent	Report is sufficient, presentation is unclear	Structured reports, communicative presentations	Professional reports, convincing & engaging presentations
Teamwork & ethics (5%)	No cooperation, bad ethics	Unbalanced cooperation	Good cooperation, ethics maintained	Very solid cooperation, exemplary ethics

Final score: Each aspect is scored 1–4, multiplied by the weight, and then added up. Convert scores to categories: 85–100 = Very Good, 70–84 = Good, 55–69 = Sufficient, <55 = Poor.

OBE Alignment Explained

This rubric is designed to assess achievement learning outcomes Problem formulation assesses critical thinking skills, formula innovation measures creativity, experimental design assesses problem-solving skills, data acquisition, analysis, and interpretation assess scientific competence and application of postharvest physiology knowledge, scientific communication assesses scientific literacy, teamwork and ethics assess professional attitudes. This OBE-based assessment ensures that students not only understand the concepts but are also able to generate real, applicable solutions to postharvest problems.

12.4 Project 4: Sensor-Based Smart Packaging Innovation Design

Project Description

Students are asked to design innovative smart packaging designs equipped with simple sensors to monitor the freshness of local fruits or vegetables. This project emphasizes understanding post-harvest physiology, packaging technology, and the application of innovation principles based on real-world problems in the field. Students may use sensor concepts based on color indicators, natural biosensors, or simple digital technologies (e.g., humidity or ethylene gas sensors). The final product is a smart packaging prototype (laboratory scale) along with a scientific report explaining the sensor's working mechanism, benefits to product quality and safety, and potential applications in the food supply chain.

Learning objectives

A. Students are able to explain basic principles smart packaging and sensors in post-harvest.

B. Students are able to design innovative packaging designs that are applicable and based on the needs of fresh products.

C. Students are able to integrate post-harvest physiology concepts (respiration, humidity, ethylene gas) with sensor technology.

D. Students are able to present design results in the form of prototypes, reports and presentations with strong scientific arguments.

Table 6. OBE Assessment Rubric

Assessment Aspects	Achievement Indicators	Score 1 (Less)	Score 2 (Enough)	Score 3 (Good)	Score 4 (Very Good)
Problem Identification and Relevance(20%)	Able to explain the problems of conventional packaging and the need for smart packaging innovation.	The problem is irrelevant or very general.	Mentions the problem but not in depth.	State the problem clearly and relevantly.	The problem analysis is very sharp, contextual, and based on literature data.
Design Creativity and Innovation(25%)	The ability to create new ideas in packaging design with sensors.	The design is not original, it is a complete copy.	There is a little innovation but it is still generic.	The innovation is quite clear and applicable.	Unique, creative innovation with potential for real implementation.
Integration of Postharvest Physiology Concepts and Sensor Technology(20%)	The relationship between post-harvest scientific principles and sensor design.	There is no integration.	Partial but inconsistent integration.	The integration is quite clear, there is a physiological and sensory relationship.	Very strong integration, explaining detailed scientific mechanisms.
Prototype Feasibility and Methodology(15%)	Packaging prototype design methodology.	There is no methodology.	The methodology exists but is not systematic.	Systematic and realistic methodology.	The methodology is detailed, realistic, and takes into account technical-economic aspects.
Presentations and Reports(10%)	Quality of scientific communicatio	Not systematic, lots of	Quite systematic but minimal	Good, systematic, with	Very good, clear, visually appealing, up

Assessment Aspects	Achievement Indicators	Score 1 (Less)	Score 2 (Enough)	Score 3 (Good)	Score 4 (Very Good)
	n in reports and presentations.	mistakes.	supporting data.	adequate references.	to date and relevant references.
Teamwork and Academic Ethics(10%)	Collaboration, attitude, and academic honesty.	No cooperation, plagiarism.	Minimal cooperation, uneven contributions.	Cooperation is quite good with member contributions.	Excellent cooperation, ethical, equal contribution, plagiarism free.

Rubric Explanation

This rubric is designed according to the OBE approach with an emphasis on learning outcomes. In the problem identification aspect, students are guided to analyze real needs in the fresh produce supply chain so that the resulting innovations are relevant. Creativity and innovation emphasize originality of ideas and the courage to explore sensor technologies that are appropriate to local conditions. The integration of post-harvest physiology concepts tests students' understanding in connecting the principles of respiration, humidity, or ethylene release with sensor design in packaging. Methodological feasibility emphasizes a systematic approach in prototyping, both from a technical and application perspective. Presentations and reports ensure students are able to communicate the results of innovations using good scientific language. Meanwhile, the teamwork aspect assesses attitudes, ethics, and fair contributions between members in completing the project.

12.5 Project 5: Horticultural Cold Chain Simulation

Project Description

Students were asked to carry out a cold chain simulation for horticultural products, such as leafy vegetables, tropical fruits, or cut flowers, from post-harvest to distribution to consumers. This project aims to provide students with an understanding of the importance of controlling temperature, humidity, and handling during transportation to maintain the quality of horticultural products. Simulations can include cold chain flow designs in the form of schematics, temperature monitoring tables, cooling energy calculations, and simple modeling using literature data or field measurements. The final product is a written report, poster, or presentation explaining the cold chain design, supporting technologies (pre-cooling, cold storage, refrigerated transport), and an analysis of potential quality losses if the cold chain is broken.

Learning objectives

A. Students are able to explain the concept and importance of the cold chain in horticultural products.
B. Students are able to design a simulation of the horticultural distribution flow with a cold chain system that suits their needs.
C. Students are able to analyze product quality if the cold chain is not optimal.
D. Students are able to integrate post-harvest physiological data (respiration, transpiration, ethylene) with low-temperature storage strategies.
E. Students are able to present simulation results in a scientific format with clear arguments and visualizations.

Table 7. OBE Assessment Rubric

Assessment Aspects	Achievement Indicators	Score 1 (Less)	Score 2 (Enough)	Score 3 (Good)	Score 4 (Very Good)
Understanding the Cold Chain Concept(20%)	Explain the basic principles and role of the cold chain.	The explanation is irrelevant or erroneous.	Very general explanation without examples.	Clear explanation with limited examples.	Very in-depth explanation, supported by the latest and applicable literature.
Cold Chain Simulation Design(25%)	Distribution flow design, cold chain	There is no design or it is very	The design exists but lacks detail.	The design is quite detailed and	The design is very detailed, innovative, and takes into

Assessment Aspects	Achievement Indicators	Score 1 (Less)	Score 2 (Enough)	Score 3 (Good)	Score 4 (Very Good)
	scheme, technology selection.	simple.		realistic.	account real field conditions.
Integration of Postharvest Physiology Concepts(20%)	The relationship between respiration, transpiration, ethylene and low temperatures.	There is no integration of concepts.	Integration exists but is shallow.	Integration is quite good with clear relationships.	Very strong integration, in-depth scientific analysis.
Risk and Sustainability Analysis(15%)	Evaluate the impact if the cold chain is broken and the potential loss of quality.	No risk analysis.	A superficial analysis only mentions general disadvantages.	Quite detailed analysis with product examples.	The analysis is very detailed, including simulation/literature data, as well as sustainability solutions.
Presentations and Reports(10%)	Preparation of scientific reports and presentations.	Not systematic, lots of mistakes.	Quite systematic, minimal visuals/data.	Systematic, self-explanatory, with references.	Very systematic, attractive visualizations, comprehensive data, up-to-date references.
Team Collaboration and Academic Ethics(10%)	Member involvement and academic honesty.	No cooperation, plagiarism.	Unequal contributions.	Good cooperation, fair contribution.	Very solid cooperation, equal contributions, plagiarism free.

Rubric Explanation

This rubric is designed to measure achievement learning outcomes OBE-based. Understanding the cold chain concept assesses students' mastery of the basic theory of post-harvest cooling. The simulation design emphasizes applied thinking skills in designing efficient horticultural distribution. The integration of post-harvest physiology concepts ensures students are able to connect aspects of respiration, transpiration, and ethylene with the need for low-temperature storage. Risk analysis hones students' critical thinking skills in identifying potential quality losses and seeking sustainable solutions. Presentations and reports measure scientific communication skills, while the team collaboration aspect assesses cooperation, responsibility, and academic integrity.

CHAPTER 13
Conclusion and Direction of Development

This final chapter summarizes the overall discussion on postharvest physiology and technology presented previously, while emphasizing the direction of future development within the context of Outcome-Based Education (OBE). The summary of postharvest physiology and technology highlights the basic principles underlying postharvest quality control of agricultural products, from respiration and transpiration to the application of modern technology to maintain product quality, safety, and economic value. Furthermore, the integration of postharvest science and technology is considered crucial to supporting food sustainability, as it connects biological understanding with relevant technical innovations in addressing global challenges such as climate change, supply chain efficiency, and yield loss reduction. Ultimately, the application of OBE is key to ensuring that graduates not only master theoretical concepts but also possess practical, innovative, and competitive skills to meet the needs of the modern food industry and support national and global food security.

12.1 Summary of Postharvest Physiology and Technology

Postharvest physiology is an essential foundation for understanding how horticultural products undergo changes after harvest, including physiological, biochemical, and physical aspects. Postharvest respiration, transpiration, and metabolic activity play a significant role in determining the rate of quality decline and shelf life. Climacteric fruit tends to experience a surge in respiration and ethylene production, which accelerates ripening, while nonclimacteric fruit generally experiences slower changes. A thorough understanding of these mechanisms allows for the design of appropriate handling strategies to maintain product freshness during storage and distribution to consumers.

Environmental factors also significantly influence the rate of deterioration of horticultural products. Temperature, relative humidity, and atmospheric conditions are external variables that regulate the intensity of respiration and transpiration. Products stored at high temperatures will rapidly degrade, while storage at low temperatures can extend shelf life by suppressing metabolic activity. However, temperatures that are too low can trigger chilling injury in tropical commodities, so control strategies must be tailored to the physiological characteristics of each product. Thus, postharvest physiology provides a scientific basis for determining optimal storage environmental parameters.

Post-harvest technology is developed by utilizing the fundamentals of physiology to minimize damage and maintain quality. Various technologies such as refrigeration, packaging, modified atmospheres, and physical and chemical treatments are applied to extend shelf life. Active or smart packaging technology, for example, can create a stable microenvironment for products, thereby maintaining quality. Furthermore, the application of sanitation, disinfectants, and edible coatings based on natural ingredients is also effective in reducing water loss, suppressing microbial growth, and increasing product safety. This approach aligns with consumer demands for products that are safe to consume and environmentally friendly.

The integration of postharvest physiology and technology not only provides benefits in terms of quality and safety but also has significant socioeconomic impacts. Proper postharvest handling can reduce yield losses, increase sales value, and strengthen the competitiveness of horticultural products in domestic and international markets. High-quality products also support food security by ensuring the availability of fresh food throughout the year. This summary demonstrates that postharvest physiology and technology complement each other and need to be developed in an integrated manner to produce an efficient, sustainable, and innovative postharvest system.

13.2 Integration of Science and Technology for Food Sustainability

The integration of post-harvest science and technology is key to achieving food sustainability, as horticultural product management must combine biological understanding with appropriate technological application. Knowledge of post-harvest physiology enables control of post-harvest respiration, transpiration, and metabolism, while post-harvest technology provides practical tools to maintain product quality, minimize yield losses, and extend shelf life. The synergy between the two results in more effective post-harvest management strategies, enabling fresh produce to reach consumers in optimal condition and with high economic value.

The development of modern technologies, such as smart packaging, Internet of Things-based sensors, and real-time cold chain monitoring systems, demonstrates how the integration of science and technology can deliver innovations that improve supply chain efficiency. With precise monitoring, the risk of damage can be minimized, product distribution more controlled, and quality maintained. Furthermore, the implementation of environmentally friendly technologies, such as natural edible coatings, biodegradable packaging, and energy-efficient storage systems, emphasizes the importance of ecological sustainability at every stage of the post-harvest process.

This integration also strengthens national food security by ensuring the availability of fresh horticultural products year-round without compromising nutritional or organoleptic quality. Proper handling helps reduce post-harvest losses, increases distribution efficiency, and ensures food stability amidst continued population growth. Thus, the integration of post-harvest science and technology contributes directly to meeting the community's nutritional needs in a more equitable and sustainable manner.

In addition to the benefits of food quality and security, the integration of post-harvest science and technology has a significant socioeconomic impact. Farmers and businesses can improve product competitiveness through innovations based on the physiological characteristics of commodities, thereby increasing product sales value and broadening market access. Consumers also benefit from safer, healthier, and longer-lasting products. Overall, this integration confirms that the combination of post-harvest science and innovative technology is a crucial foundation for an efficient, sustainable, and adaptive food system to future global challenges.

13.3 OBE's Contribution to Producing Competent and Innovative Graduates

The Outcome-Based Education (OBE) approach plays a central role in developing competent and innovative graduates in postharvest physiology and technology. With OBE, learning focuses on achieving clear and measurable learning outcomes, enabling students to not only understand theoretical concepts but also apply their knowledge in real-world contexts. Projects, practicums, and simulations implemented in the postharvest curriculum enable students to experience hands-on learning, honing analytical, problem-solving, and data-driven decision-making skills. This fosters critical and creative thinking, which are essential to addressing the dynamics of the modern food industry.

OBE encourages students to develop multidimensional competencies, from mastering the principles of post-harvest physiology to applying cutting-edge technology to maintain the quality and safety of horticultural products. Through project-based assignments such as cold chain control, edible coating application, and smart packaging design, students are trained to integrate scientific knowledge with technical practice. This approach emphasizes active, collaborative, and problem-based learning, ensuring graduates are more employable and able to adapt to various industry demands and evolving technological innovations.

In addition to developing technical skills, OBE also emphasizes essential soft skills for postharvest professionals, including teamwork, scientific communication, ethics, and project management. Students learn to systematically design, implement, and evaluate projects while maintaining academic ethical standards. This approach equips graduates with the capacity to work collaboratively, lead teams, and communicate effectively, enabling them to communicate scientific findings and technical recommendations to diverse stakeholders in the agriculture and food sector.

Overall, OBE's contribution to postharvest physiology and technology education is evident in the graduates' ability to become competent, innovative, and adaptable professionals. This approach ensures that students not only master theory but also translate it into practical solutions relevant to the needs of industry and society. Thus, OBE produces graduates who are ready to face global challenges in the food system, capable of developing new innovations, and contributing significantly to improving food quality, safety, and sustainability.

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ATTACHMENT

L1. Example of Course RPS

1. Course Identity

- Course Name: Postharvest Physiology and Technology
- Course Code: FPT-401
- Study Program: Agrotechnology / Food Technology
- Semester: 5
- Credits: 3 (2 theory, 1 practical)
- Instructing Lecturer: Prof. Dr. Ir. I Ketut Budaraga, MSi. CIRR

2. Course Description

This course discusses the principles of post-harvest physiology in horticultural commodities, quality control technology, safety, and shelf life of fresh produce. The material is presented in an integrated manner, combining theory and laboratory practice, using an Outcome-Based Education (OBE) project approach to enhance students' competencies in the analysis, innovation, and application of post-harvest technology.

3. Course Learning Outcomes (CPMK)

After taking this course, students are expected to be able to:

A. Explains the basic concepts of post-harvest physiology, including respiration, transpiration, and metabolic changes.
B. Identify environmental and technological factors that influence the quality and shelf life of horticultural products.
C. Design and implement simple experiments or projects related to post-harvest quality control.
D. Evaluate and analyze experimental results or post-harvest data scientifically.
E. Presenting scientific reports and project results systematically, ethically and communicatively.

4. Learning Strategy

- Face-to-face lectures and interactive discussions
- Laboratory practicum and post-harvest technology simulation
- Case study based innovation project
- Presentation and discussion of project results

5. Assessment Method

Assessment Aspects	Weight	Assessment Form	Criteria
Presence and participation	10%	Observation	Actively discuss and participate in practicals
Individual assignments	20%	Short report	Conceptual understanding and analytical accuracy
Practicum	25%	Reports and experimental results	Accuracy, mastery of methods, data interpretation
Group project	30%	Project presentations and reports	Creativity, innovation, integration of science and technology
Final exam	15%	Written test	Understanding basic concepts and their applications

6. Main Material and Time Allocation

Sunday	Topics	Form of Activity	Expected Outcome
1	Introduction: Scope of Postharvest and OBE	Interactive lectures	Students understand the objectives of the course and OBE
2-3	Postharvest physiology: respiration and transpiration	Lectures & discussions	Students are able to explain post-harvest physiological processes
4-5	Quality and damage of horticultural products	Practicum	Students are able to identify damage factors
6-7	Storage and quality	Practicum &	Students are able to apply

Sunday	Topics	Form of Activity	Expected Outcome
	control technology	case studies	technology to maintain quality
8-9	Post-harvest packaging: conventional and smart	Group project	Students design sensor-based packaging innovations
10-11	Cold chain and horticultural distribution	Simulation	Students understand the concept of refrigerated distribution
12-13	Project evaluation and presentation	Group presentation	Students are able to present project results scientifically
14	Final exam	Written test	Students demonstrate a thorough understanding of the material

7. Main References

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L2. Example of an OBE-Based Project Assessment Rubric

Subject: Postharvest Physiology and Technology
Type of activity: Postharvest Projects (e.g. Fruit Respiration Analysis, Cold Chain Simulation, Edible Coating Application)
Assessment Team: Supporting lecturer

Assessment Aspects	Description	Score 1 (Less)	Score 2 (Enough)	Score 3 (Good)	Score 4 (Very Good)	Weight
Concept Understanding	Mastering the principles of post-harvest physiology and project-related technologies	Not understanding the basic concepts	Understanding basic concepts in a limited way	Understand the concept quite clearly	Understand the concept in depth and be able to relate theory to practice	25%
Project Design	Design of innovation experiments/projects according to OBE objectives	Design is unclear or irrelevant	Simple design, some goals achieved	The design is quite complete, some are innovative	The design is complete, creative and meets OBE goals	20%
Project Implementation	Ability to carry out experiments/projects according to procedures	Not following the procedure, the results are invalid	Performed some procedures, limited results	Performing the procedure correctly, the results are quite valid.	Very precise execution, accurate and consistent results	20%
Data Analysis and Interpretation	Ability to analyze results and draw scientific conclusions	Analysis is unclear or incorrect	Simple analysis, less precise conclusion	The analysis is quite clear and the conclusions are logical.	In-depth analysis, precise conclusions, clear implications	20%
Presentations and Reports	Presentation of scientific reports and	Unsystematic report,	The report is quite	Clear and complete	Very systematic	10%

Assessment Aspects	Description	Score 1 (Less)	Score 2 (Enough)	Score 3 (Good)	Score 4 (Very Good)	Weig ht
	project presentations	unclear presentatio n	systematic, the presentation is standard.	report, interesting presentatio n	report, attractive visualizatio n, communica tive	
Team Collaboration and Ethics	Participation, cooperation, and academic integrity	No participatio n, plagiarism	Limited participation , uneven contribution s	Good participati on, equal contributio n	Very good cooperatio n, equal contributio n, ethics maintained	5%

Information:

- The score for each aspect is assessed from 1 to 4.
- The final score is calculated from the sum of the weights × scores of each aspect.
- This rubric is designed to support Outcome-Based Education (OBE), thus emphasizing conceptual mastery, practical skills, analytical abilities, and communication and collaboration competencies.

L3. Practical Guide

Subject: Postharvest Physiology and Technology
Semester: 5
Credit Weight: 3 (2 theory, 1 practical)
Supporting lecturer: Prof. Dr. Ir. I Ketut Budaraga, MSi. CIRR

A. Objectives of the Practical

1. Students are able to understand the principles of post-harvest physiology, including respiration, transpiration, fruit ripening, and changes in vegetable quality.
2. Students are able to apply post-harvest technology to maintain quality, extend shelf life, and reduce yield losses.
3. Students are able to design and implement post-harvest experiments or projects systematically.
4. Students are able to analyze data from practical work and draw scientific conclusions.
5. Students are able to present practical reports systematically and communicatively.

B. Practical Material

1. Analysis of respiration rate of climacteric and non-climacteric fruit.
2. The effect of storage temperature on the quality of leafy vegetables.
3. Application of natural edible coating on local fruit.
4. Design a cold chain scheme for the distribution of horticultural products.
5. Sensor-based smart packaging innovation design.

C. Practical Method

1. Laboratory demonstration and direction by lecturer.
2. Group practicum of 3–4 students per group.

3. Observation, measurement, and data recording using standard laboratory instruments.
4. Discussion of data analysis in groups and consultation with lecturers.
5. Preparation of scientific reports and presentation of practical results.

D. General Practical Steps

1. Preparation of Tools and Materials: Make sure all measuring instruments, sample materials, and storage media are ready for use.
2. Initial Observations: Record the initial condition of the product (color, texture, weight, water content, degree of ripeness).
3. Implementation of Treatment: Apply the treatment according to the lab instructions (e.g. different storage temperatures, coating applications, or packaging).
4. Periodic Measurement: Perform measurements of physical, chemical, and physiological parameters at specified time intervals.
5. Data Logging: Record all results systematically on the observation sheet.
6. Data analysis: Calculate the respiration rate, transpiration, quality changes, and interpret the results.
7. Group Discussion: Compare results between groups and discuss differences, causes, and implications for post-harvest technology.
8. Reports and Presentations: Compile a scientific report that includes objectives, methods, results, analysis, and conclusions, prepare a group presentation.

E. Practical Assessment

Assessment Aspects	Weight	Information
Presence and participation	10%	Actively participate in practicals and discussions
Data recording and processing	25%	Neat, complete, and accurate
Implementation of procedures	25%	Comply with procedures and be safe
Analysis and interpretation	25%	Correct, logical, and in accordance with physiological concepts
Reports and presentations	15%	Systematic, clear, and communicative

F. Practical Ethics

- Use laboratory equipment according to instructions.
- Maintaining laboratory cleanliness and safety.
- Respect group work and share tasks fairly.

About Author

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Prof. Dr. Ir. I Ketut Budaraga, MSi. CIRR was born in Bulian Village, Kubutambahan District, Buleleng Regency on July 22, 1968. Graduated from Elementary School No. 1 Bulian in 1982, SMP 1 Singaraja in 1984. SMA Lab Unud Singaraja in 1987. Continued to the Faculty of Agriculture, Mataram University in 1987 and graduated in 1992. Continued his S2 education in 1995 to Postgraduate study program Post Harvest Engineering IPB graduated in 1998. Given the opportunity to continue to S3 Agricultural Science graduated in 2016. Appointed as a PNSD Lecturer to Kopertis Region X Padang placed at Ekasakti University in the Faculty of Agriculture in the Agricultural Product Technology study program, most recently given the trust to become a professor in the field of Processing Technology starting August 1, 2023.

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