

Chapter 5:

Curcumin-Infused Lipid Films for Active and Smart Packaging: A Sustainable Solution

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Packaging plays a vital role in preserving product quality, extending shelf life, and enhancing consumer appeal. In recent years, there has been a growing emphasis on innovation within the packaging industry to meet evolving consumer demands and environmental concerns. This chapter explores the integration of curcumin as a material selection in smart and active packaging, aiming to enhance both functionality and sustainability. Beginning with an overview of packaging materials, the discussion delves into the emergence of smart packaging, which incorporates technologies to monitor and improve product conditions. Active packaging is then introduced, highlighting its ability to actively interact with the packaged product to extend its shelf life or improve safety. The criteria for selecting active packaging materials are examined, emphasizing the importance of barrier properties and compatibility. Intelligent packaging is discussed as a subset of smart packaging, focusing on its ability to provide additional information or functionalities to consumers. The relationship between packaging and color perception and the use of colorants in packaging materials is explored. The chapter addresses concerns regarding synthetic colourants and their potential health implications, prompting the exploration of alternative options such as curcumin. Transitioning to specific product categories, the discussion encompasses both bar soap and liquid soap packaging, examining factors such as stability, foaming abilities, and the influence of surfactants. Within this context, the potential of curcumin as a material selection is investigated, considering its antimicrobial properties, antioxidant benefits, and biodegradability. Overall, this chapter provides a comprehensive overview of packaging innovations, culminating in a detailed examination of curcumin as a promising material for smart and active packaging applications. By embracing these innovations, the packaging industry can not only meet consumer expectations but also contribute to sustainable practices and environmental stewardship.

1 Introduction

Packaging is a cornerstone of modern commerce, ensuring the safe transportation, preservation, and presentation of goods. In recent years, the industry has witnessed a paradigm shift towards innovative solutions that not only fulfil traditional functions but also address emerging consumer preferences and environmental concerns. Curcumin, a natural compound found in turmeric, has garnered interest in packaging innovations due to its antioxidant, antimicrobial, and bioactive properties (Roy, Priyadarshi, Ezati, & Rhim, 2022). The compound and functional group of curcumin has potential value to integrate with lipids for sustainable application in smart packaging such as encapsulation in lipid-based systems, incorporation into lipid-based edible coating or conjunction with lipid sensors in smart packaging indicators. This chapter explores the forefront of packaging innovation, with a particular focus on the integration of curcumin as a material selection in both smart and active packaging applications. Through an examination of the evolving landscape of packaging materials and technologies, alongside a consideration of consumer perceptions and sustainability imperatives, we delve into the potential of curcumin to revolutionize the packaging industry. To achieve the aims of this chapter, several objectives are outlined. These include examining the use of curcumin as a material in smart and active packaging and identifying its potential to enhance both functionality and sustainability.



2 Packaging

2.1 Packaging Material

'Packaging' is a type of art, science, and technology concerned with ensuring a product's quality, wholesomeness, integrity, and safety. It is necessary for preparing goods for transportation, distribution, storage, retailing, and subsequent end-use. It is also required to ensure the safe delivery of products to consumers, which includes a technological, commercial function aimed at reducing delivery costs while increasing sales (Coles & Kirwan, 2011; Pal, Devrani, & Hadush, 2019). Since the dawn of the globalization and urbanization eras, consumer demand for safe and high-quality foods has been on the rise. Once properly packaged, food will depend on the composition and a variety of extrinsic factors, which are required to last from a few hours to days, and even months, depending on its shelf-life. A food product may come into contact with physical, chemical, or biological agents during handling, preparation, or transportation. Food products are packaged to keep their goodness and freshness. It can aid in avoiding the spread of contamination by keeping in contact with other food products or material parts that contribute at any point of the food supply chain. As a result, today's market demands requirements and specifications for food packaging and labelling. Food packaging is an essential component of the food supply chain that serves as a barrier layer against contamination, the external environment, and mechanical damage during transport, all of which have a negative impact on product quality. It also serves as a preventive tool, requiring products to be sealed at all distribution stages until they are opened by the end user, ensuring zero spillage and checking for tampering issues. Food packaging primarily serves as an identification and communication tool between the producer and the consumer, representing product details such as nutritional facts, health benefits, directions for use and storage, place of manufacture, manufacturing date, expiry date/best before date, and other relevant information. Furthermore, appropriate packaging that demonstrates its marketing tool that can be linked with an appeal to different classes of consumers that include age, gender, culture, and other factors is required. The purpose of packaging itself can aid in the optimization of a tool that can assist in the purchase of a desired quantity of produce while also assisting in the reduction of waste (Sohail, Sun, & Zhu, 2018).

In 2009, the food packaging industry was one of the largest sectors within the packaging industry. According to Renata Dobrucka (2014), it was estimated that the value of active packaging in the global market was US\$6.4 billion in 2013, accounting for 26.9% of the packaging market share. In contrast, intelligent packaging was estimated to be worth US\$2.3 billion, characterized by its active function in extending the shelf life of food products. Packaging is defined as the process of enclosing food to protect it from tampering or contamination from physical, chemical, and biological sources. It helps maintain the benefits of food processing after the process is complete, ensuring that food can travel safely over long distances from its point of origin while remaining wholesome at the time of consumption. The primary purpose of food packaging is to protect the food from oxygen, water vapour, ultraviolet light, and both chemical and microbiological contamination (Drago et al., 2020). Active packaging was originally used successfully to increase the shelf life of processed foods and meet consumer demands in terms of providing high-quality products that are also fresh and safe.

2.2 Smart Packaging

Smart packaging technology offers an innovative solution to address various challenges within the packaging industry. It combines both active and intelligent systems to enhance shelf life and communicate food quality to consumers throughout the distribution and supply chain process. This approach improves traditional packaging by integrating features that allow it to detect and communicate changes in internal and external conditions. In a broader context, packaging solutions can be classified into two categories: active packaging and intelligent packaging. Active systems primarily work to extend shelf life by interacting with the product or its environment, while intelligent systems focus on conveying information to consumers, providing insights about product quality.

This advanced technology is increasingly used in food packaging, where it can inform consumers about product integrity and authenticity, while also preventing spoilage. Additionally, it can enhance attributes such as taste and appearance. Beyond this, such systems can deliver crucial food-related information and respond to environmental or product changes. One of its most vital functions is ensuring seal integrity, which can also serve as a deterrent to counterfeiting.

From previous studies, smart packaging is defined as the packaging that includes both active and intelligent systems. It has the potential to monitor the changes during storage (increase/decrease in temperature or humidity) and works to slow down the quality degradation. By using the compounds from active packaging (antioxidants, emitters of carbon dioxide, humidity, antibacterial agents, oxygen scavengers, and ethylene with joining with intelligent devices that acquire the concept named 'smart packaging'. (Schaefer & Cheung, 2018; Vanderroost et al., 2014; Latos-Brozio & Masek, 2020; Yucel, 2016). Smart packaging covers devices that can be used for heating or cooling food inside and shows on the electronic display of the nutritional information in real-time (Opara, 2013). It is included with a device incorporated in the package that can be used to change the temperature inside. It was developed for bottles, cans, or carton packages. It can lower the product's temperature with 18 °C in a short time, within 2 or 3 minutes before it is consumed. The concept behind this packaging involves absorbing heat from the liquid inside. This is achieved by releasing pressurized water from a vinyl bag, which evaporates immediately, creating vapors that help to cool the contents (Brody, 2002).

2.3 Active Packaging

Active Packaging is an innovative concept that can be defined as integrating specific materials into packaging to help maintain and extend the shelf life of products and it goes beyond serving as a passive barrier to external factors by actively contributing to food preservation, performing additional functions that enhance the product's quality and longevity (Mane, 2016). This is particularly important in the area of fresh and extended shelf-life foods.

2.4 Criteria of Active Packaging Materials

Molecular oxygen (O₂) can be reduced to a variety of intermediate species by adding between one and four electrons, forming superoxide, hydroxyl radical, hydrogen peroxide, and water. Except for water, the remaining three intermediate species are very reactive. Reactive oxygen species, being free radicals, participate in autocatalytic oxidative reactions. Oxygen scavengers offer several advantages, as noted by Michiels et al. (2017). They prevent oxidation phenomena such as rancidification of fats and oils, which can cause off-odors, off-flavors, and changes in the characteristic colors of food, as well as the loss of oxygen-sensitive nutrients like vitamins A, C, and E, and unsaturated fatty acids. Additionally, they inhibit the growth of aerobic microorganisms, reduce or eliminate the need for preservatives and antioxidants by enhancing the appeal of "fresh" or "natural" products, and provide an economical and efficient alternative to modified atmosphere or vacuum packaging. The use of these systems, either alone or in combination with other traditional packaging systems, and the use of modified atmospheres can extend a food product's commercial life.

Since the permeability of CO₂ is 3 to 5 times higher than that of O₂ in most plastic films, it must be continuously produced to maintain the desired concentration within the package. The oxygen-free environment alone is insufficient to retard the growth of *Staphylococcus aureus*, *Vibrio species*, *Escherichia coli*, *Bacillus cereus*, and *Enterococcus faecalis* at ambient temperatures. O₂ and CO₂ absorbers inhibited the growth of *Clostridium sporogenes* (Alehosseini & Jafari, 2019). The control of ethylene in stored conditions plays a key role in prolonging the postharvest life of many types of fresh produce (Hu et al., 2019). Another way of tackling the problem of microbial growth is by the use of nonvolatile antimicrobial additives. Many preservatives (sorbic acid, benzoic acid, propionic acid, and its salts, or bacteriocins such as nisin, natural spices, silver ions, chelators, etc.) are added to plastic films and materials used as antimicrobials. However, these nonvolatile antibacterial require direct contact with the food to be active

(Ouattara et al., 2000). Oxidation of fats is one of the most important mechanisms leading to food spoilage, second only to the growth of microorganisms. The oxidation of lipids in food reduces shelf-life due to changes in taste and/or odour, deterioration of the texture and functionality of muscle foods, and a reduction in nutritional quality. Oxidation of food can be avoided using oxygen scavengers and antioxidant agents in the packaging. Such packaging is intended to prevent or slow down the oxidation reactions that affect the quality of food (Pereira et al., 2010).

2.5 Intelligent Packaging

The indicators should be easily activated and exhibit a change (or show an indication) that is easily measurable and irreversible, time- and temperature-dependent changes must be reproducible and ideally matched or readily correlated with the food quality, and also provide information regarding the status of the package (Yildirim et al., 2018). Intelligent packaging has been defined as packaging systems that monitor the condition of packaged foods to give information about the quality of the packaged food during transport and storage (Silva et al., 2019). The visual indicators change colour in response to cumulative exposure to temperature. The main mechanisms of action include enzymatic reactions, polymerization, or chemical diffusion (Welt et al., 2003). Most O₂ or CO₂ indicators change colour as a result of chemical or enzymatic reactions. A colour change indicates when the oxygen concentration exceeds the limit established in a sealed food package (Hu et al., 2009). Indicators based on colour changes due to changes in pH are of great potential use as indicators of microbial metabolites and ripeness (Nopwinyuwong et al., 2010).

2.5.1 Polymers

Polymers have a wide range of applications, from plastics as packaging materials, to implants in biomedical fields. However, these convenient petrochemical-based materials, which are non-biodegradable and designed for immediate disposal, have caused a lot of pollution problems ever since they became dominant in the marketplace around 1940 (Jambeck et al., 2015). That is why more research is being carried out on biodegradable polymers to serve as an alternative to their petrochemical-based counterparts in every field possible (Tsuji, 2014).

Poly(lactic acid) (PLA) is a type of biodegradable polymer that has gained a significant increase in popularity in different fields, including biomedical, pharmaceutical, and environmental. It is derived from renewable resources such as corn starch and is seen as a great alternative for petrol-based polymers. The application of this polymer looks promising in many fields, especially in the food industry field (Krishnan et al., 2015). With curcumin having properties such as antimicrobial, antioxidant, anti-inflammatory, and other health benefits, it would be a great initiative to try and incorporate this almost-miraculous compound into polymers that could be useful not just for consumption but also for food packaging purposes). Fortunately, Poly (lactic acid) ,known as PLA, is a green polymer from renewable resources (manufactured by the polymerization of lactic acid monomers derived from the fermentation of starch feedstocks) which were biodegradable and compostable (bioplastic). However, it has lower strength, is brittle, flammable, and has a high permeability to most gases and solvents compared to metal and ceramics, limiting its application in the industry (Shirai et al., 2013).

Poly (vinyl alcohol) (PVA) is widely used in industries with diverse applications such as the coating industry, biopolymer film, medical industries, and food processing, and it can also be used as a hydrate inhibitor in the oil and gas industries. PVA is a synthetic water-soluble polymer. It is composed of biodegradable carbon atoms (Chiellini et al., 2003; Riew et al., 1976; Aina et al., 2014; Halima et al., 2016), with aerobic and anaerobic conditions. There are two types of PVA, which are fully zhydrolyzed and partially hydrolyzed. PVA is known as non-biodegradable (Alves et al., 2011). PVA is a type of water-soluble polymer that is included in the class of water-soluble non-ionic polymers, which belongs to a vinyl group (Moukwa et al., 1993, Sivakumar, 2010). It is non-hazardous, safe to handle, and relatively environmentally friendly (U. S. International Trade Commission, 2009). PVA is odourless, tasteless, translucent, and in the form of powder (Saxena, 2004). Fully zhydrolyzed types of PVA are soluble in hot water and have good film-forming

characteristics (insoluble in water at a lower temperature will form film) and have a property that includes a good adhesive (Chan *et al.*, 1999)

Chitin is made up of the structural material of crustaceans, fungi, and insects and is included as the second most abundant biopolymer after cellulose on Earth. Chitosan can be produced from a deacetylated derivative of chitin, which can be obtained by deacetylation of chitin. When the degree of deacetylation of chitin reaches 50%, it can be soluble in aqueous acidic media and it is called chitosan (Rinaudo, 2006). It is called a functionally versatile biopolymer due to the presence of amino groups responsible for a polymer's various properties. Chitosan has been used in various industrial applications because of its properties, which are chitosan-based flexible food packaging and edible food coatings that can compete with conventional non-biodegradable plastic-based food packaging materials. The important factor in food packaging is its barrier properties. The product could deteriorate the quality of the food by affecting the interaction between oxygen and water vapour (Srinivasa *et al.*, 2002).

3 Colourants

3.1 Packaging and Colour

Colour has its own role in demonstrating the effects of an initial acceptance or rejection of a food product (Manzoor *et al.*, 2021). Colour has been evaluated based on consumer preferences and is responsible for 62-90% of the total (Teixeira *et al.*, 2022). The colour is required to be used as one type of utilizing and maintaining a consistent colour between batches, assist in enhancing the intensity of pigments, and also assist in allowing the production of coloured products that were previously colourless, and so on (Nonglait & Gokhale *et al.*, 2024). Furthermore, in order to promote the attractiveness of food's visual aspects, colour plays a significant role in promoting the importance of food safety and nutritional quality (Zhou *et al.*, 2022). (Fig. 5.1).

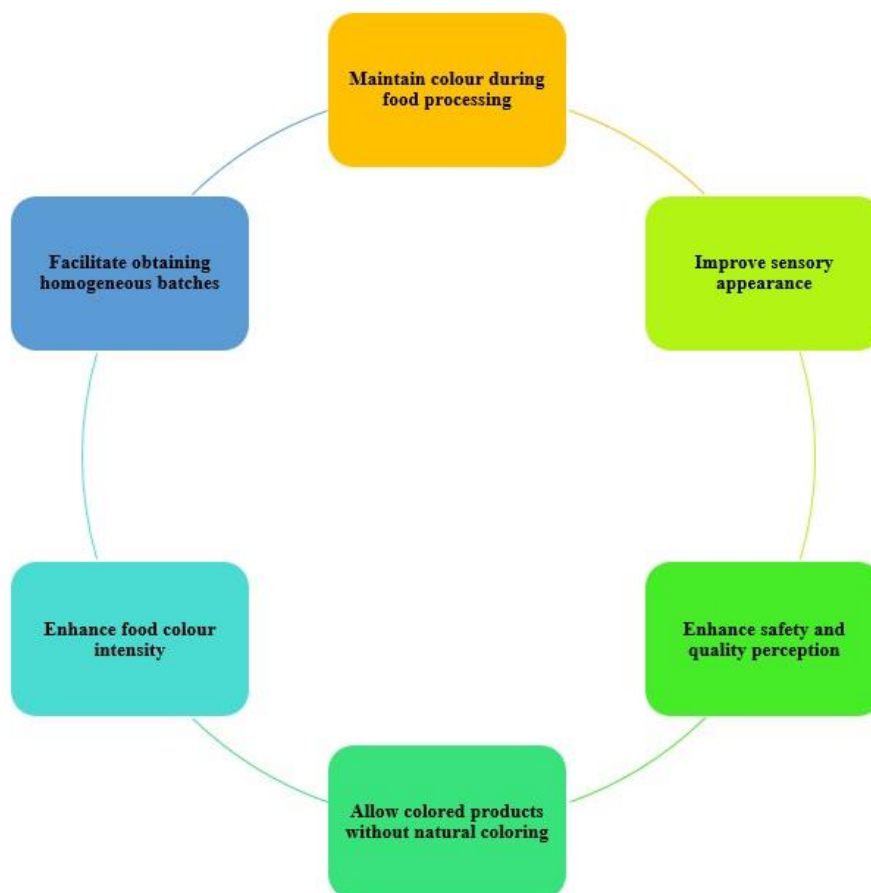


Figure 5.1: Potential advantages of using colourants in food processing

Packaging is an important application for protecting and preserving food quality and safety (Roy & Rhim, 2021). Aside from its traditional function of food protection, a food package can be used to communicate by informing consumers about its shelf life, nutritional properties, manufacturer information, storage conditions, and so on. Because of the growing consumer demand for safe, high-quality, and ready-to-eat foods, packaging technology has been improved in recent years. As can be seen in the food industry (for both food manufacturing and, more recently, food packaging), it is necessary to focus on developing highly stable, attractive colour and low-cost synthetic dyes to improve food's appearance or packaging technologies. However, the artificial colourants that are commonly used in food processing, such as Allura Red, carmoisine, Ponceau 4R, Sunset Yellow, tartrazine, quinophthalone, and Quinoline Yellow, can cause adverse effects and cause various types of health issues, including allergies, irritability, and hyperactivity, and to some extent, cancer (Roy & Rhim, 2021). Natural food colourants, as a result, can be summarised as one of the amazing interests as one of the natural additives or as indicators in food packaging to meet the demands of consumers for healthier and safer food. According to Ezati et al. (2021); natural colourants are safe and have functional properties, such as antioxidant and antimicrobial properties.

3.2 Synthetic Colourants and Health Issues

In the past few years, people have become increasingly aware of the use of natural colorants (Dweck, 2009). Consumers are more worried about the safety of synthetic colourants. Many of the approved artificial dyes are being rejected due to consumer preference and legislative action (Garcia, F. & Cruz-Remes, L., 1993). Research by Sahar and Manal (2012) demonstrated that colour additives in food can affect the liver and kidneys of rats over a 13-week period, as evidenced by changes in serum biochemistry. In addition, at a low dose of synthetic colour, the liver showed a disruption of hepatic cells near the central vein and hepatocellular damage. The results showed a line from the agreement with Sharma (1976), who claimed that synthetic colours adversely affected vital organs. Bateman et al. (2004) conducted a work on the effects of artificial food colourings and benzoate preservative challenge from the preschool children population in a general of their hyperactivity. The result showed there is a general adverse effect of artificial food colouring and benzoate preservatives on the behaviour of 3-year-old children (Sahar & Manal, 2012). It can be concluded that the children will benefit more if they do not consume artificial food colours and benzoate preservatives and were advised to remove them from their diet.

3.3 Application of colourants and packaging

The application of colorants and packaging in soap production highlights the evolving trends in consumer preferences for natural and sustainable products. Bar soaps, typically made through saponification of natural oils like coconut oil with sodium hydroxide (NaOH), have been enhanced with natural ingredients to provide antibacterial, antifungal, antioxidant, and anti-inflammatory properties, which also impact color, texture, and odor (Kole, 2005; Mukherjee et al., 2009; Prito Vidal et al., 2018). Liquid soaps, originally developed in the United States, gained popularity for their advantages over bar soaps and are now produced with surfactants and formulations that improve quality, stability, and consumer appeal (Chidi & Adebayo, 2018; El-Shattory et al., 2018). The physicochemical properties of soaps, including pH, viscosity, and stability, significantly influence their performance and consumer acceptance (Hassan et al., 2017). Factors like surfactant type and concentration, foam stability, and viscosity contribute to the effectiveness and quality of liquid soaps (Osei-Bonsu et al., 2015; Sheng et al., 2023). Advanced formulations, such as those using methyl ester sulphonate (MES), offer long-term stability and superior performance under varying conditions (Abd Maurad et al., 2017).

3.4 Curcumin as Material Selection

3.4.1 Curcumin and its Properties

Curcumin [1, 7-bis (4-hydroxy-3-methoxyphenyl)-1, 6-heptadiene-3, 5-dione] is the principal curcuminoid in turmeric which is the cause of its bright yellow colour. It is a carotenoid that can be extracted from the

rhizomes of the plant *Curcuma longa* that changes colour in alkaline conditions or high pH solution (Oglah *et al.*, 2020). Curcumin is an effective scavenger of many reactive oxygen species (ROS), including hydroxyl radicals and superoxide anions, explaining its antioxidant properties (Hewlings & Kalman, 2017). Curcumin also shows promising potential in correcting cystic fibrosis. Although the test was only observed in animals, specifically baby hamsters' kidney cells, the research showed that through oral administration, curcumin induced the functional appearance of AF508 CFTR protein, which is the affected protein in cystic fibrosis (Egan *et al.*, 2013). Curcumin is industrially produced using oleoresin of turmeric as the raw material. Even the by-products that are produced from the isolation of curcumin have been tested and proven to have antibacterial activities against a range of pathogenic and spoilage bacteria, which include *Bacillus cereus*, *Bacillus coagulans*, *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa* (Nelson *et al.*, 2017). A study using size exclusion chromatography and dynamic light scattering has shown it to be a dimer at pH 7 but changes its form to be a monomer when it reaches pH 2. The dimer at pH 7 is more stable than the monomer at pH 2 (Biswas & Chattopadhyaya, 2014). Delgado *et al.* (2016), observed that turmeric in its amorphous state was stable under storage conditions with temperatures ranging below 65.35 °C whereas Tonnesen *et al.* (1986) found that curcumin exhibited photodecomposition upon exposure to ultraviolet (UV) visible radiation. As a thin film, this photodecomposition was seen in both solution and the solid-state. The main product was formed by a loss of a couple of hydrogen atoms from the curcumin molecule, resulting in its cyclization. Curcumin could have a destabilizing effect in a mixture of other compounds due to its sensitizing properties. Curcumin, a diphenol compound with a low molecular weight that is nontoxic and hydrophobic, is insoluble in water and ether but soluble in methanol, ethanol, and dimethyl sulfoxide. It is drawn to composite film fabrication for its packaging applications because it offers additional functional features such as increased mechanical strength, UV protection, antioxidant properties, and antibacterial activity (Roy *et al.*, 2024). Curcumin exhibits a distinct pH-responsive colour change due to alterations in its predominant chemical structure under varying pH conditions. The ordered crystal structure of curcumin consists of a seven-carbon chain featuring an α,β -unsaturated diketone moiety, which is linked to two aromatic rings containing ortho-methoxy phenolic hydroxyl (-OH) groups. This unique molecular arrangement enables curcumin to interact differently across a range of pH levels, resulting in observable changes in colour (Sahne *et al.*, 2017).

Curcumin's molecular configuration is influenced by factors such as the pH of the solution, polarity, and temperature. At neutral and alkaline pH levels, the α,β -unsaturated β -diketone moiety of curcumin acts as a hydrogen donor site, leading to hydrolysis and subsequent degradation of the compound. The β -diketone chain within the curcumin molecule exists in a keto-enol tautomeric form, which varies based on the properties of the solvent. In acidic or neutral pH environments, the bis-keto form is predominant, whereas in basic pH conditions, the enolic form becomes more stable (Noureddin *et al.*, 2019).

In solutions with pH values ranging from 1 to 7, curcumin predominantly exists in its bis-keto form, which appears yellow in colour and exhibits very low water solubility. As the pH increases towards alkaline conditions, the solubility and stability of curcumin improve significantly. Under these basic conditions, the enolic form of curcumin becomes dominant. This transition is facilitated by the donation of hydrogen atoms from the central carbon (C-H bonds) to neighbouring oxygen atoms, driven by the weak delocalisation of unpaired electrons (Typek *et al.*, 2019).

3.4.2 Chemical Structures

The absorption spectra of carotenoids depend largely on the number of conjugated double bonds (c.d.b.) in their molecules. The longer the chromophore, the higher the wavelengths of maximum absorption. Acyclic carotenoids absorb maximally at longer wavelengths than cyclic carotenoids with the same number of c.d.b. in which conjugation extends into rings, due to the fact that, in the latter, there are steric strains. The UV/Vis spectrum of carotenoids is of great importance for analysts because it provides valuable information about their structure. The spectrum is due to the presence of the long chromophore of conjugated double bonds (c.d.b.). At least 7 c.d.b. are needed for a carotenoid to have perceptible colour.

Thus, a carotenoid with 7 c.d.b., has slight yellowish colour, whereas carotenoids with 3 and 5 c.d.b. are colourless (He et al., 2018).

3.4.3 Functional Groups

The functional group may also be part of the polymer main chain. It incorporated into polymer molecules for a number of reasons. The arrangement of functional groups, which include aromatic and polar groups, along a polymer backbone has a significant impact on the polymer's radius of gyration and end-to-end distance. Research indicates that the distribution of these groups plays a crucial role in determining the polymer's structural compactness. While a random distribution tends to produce the most compact structure, different distributions can lead to larger values. For instance, the largest values occur when functional groups are evenly distributed between both ends of the polymer (Apóstolo et al., 2018). Their presence may modify the physical properties, such as adhesion to a substrate or solubility in selected solvent composition, or the functional group may be essential for the polymer-forming reaction or to enable subsequent chemical interaction with other entities.

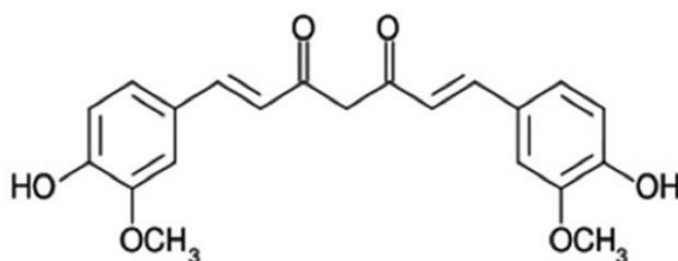


Figure 5.2: Chemical structure of curcumin (Kuttan et al., 1985)

3.5 Biological activity of curcumin

3.5.1 Antioxidant activity

In both in vitro and in vivo settings, various assays have been used to determine the antioxidant activity of curcumin. The antioxidant effect is due to its hydroxyl groups, which is directly proportional in between of functional groups and to the free radical scavenging activity of this polyphenolic compounds. The presence of one or more hydroxyl groups which showed the significant superior of antioxidant activity due to the curcumin derivative is (3,4-dihydroxycinnamoyl)-methane (Sharma, 1976). In line with, a role for the -OH group in free radical scavenging that has been proposed in other compounds for example carboxymethyl cellulose (Ezati et al., 2021). From the previous studies, the researchers have suggested that, the main role of -OH in the free-radical scavenging effect of curcumin (Chen et al., 2002). In the curcumin, the position of hydroxyl group plays a major role. It has been mentioned by Bakar et al., 2023, the 2-hydroxyphenyl group which found in the curcumin derivative bis(2-hydroxycinnamoyl)-methane showed a better antioxidant activity as compared to 4-hydroxyphenyl group which present in curcumin.

3.5.2 Antimicrobial activity

From the previous study mentioned by Chen et al., 2010, the antiviral activity of curcumin can oppose to the influenza virus. They claimed that, over 90% of the compound can help in reduced the viral population in cell culture at a treatment concentration of 30 μ M. It has been claimed that, the curcumin can prevent the spread of the influenza virus, which can interfere with cellular virus adhesion. The effect of curcumin and curcuminoids on fungal strain *Candida albicans* (Zhang et al., 2012). The antifungal effect of curcumin was powerful as compared to demethoxycurcumin. It was claimed that, in curcumin, the methoxyl group makes it more lipophilic, which resulted in uninterrupted entry into the fungal cell membrane, which can

prevent its growth. From the previous study conducted by Adamczak, et al., 2020, they performed the experiment on the antimicrobial activity from the turmeric against more than 100 pathogens that are belonging to 19 species. It is included with molds and molds and a lot of Gram-positive and Gram-negative bacteria. It is proven that; the curcumin has a higher antimicrobial tendency against Gram-positive bacteria as compared to Gram-negative bacteria.

3.5.3 *Curcuma xanthorrhiza* Roxb

Curcuma xanthorrhiza Roxb. (Family: Zingiberaceae) is a native Indonesian that is high in the valuable plant known locally as 'Temu lawak' or Java turmeric. It is predominantly grown in Indonesia and other Southeast Asian countries such as Malaysia, Thailand, Vietnam, and the Philippines (Salleh *et al.*, 2016). Zingiberaceae is one of the most diverse plant families in tropical and subtropical areas, with approximately 19 genera and 375 species found in Indonesia (Hartati *et al.*, 2014). Because of its biological properties, *C. xanthorrhiza* is commonly used as an Indonesian herbal supplement and medicine to treat or control a variety of illnesses and disorders dating back to ancient times, such as lack of appetite, stomach illness, liver ailments, constipation, blood diarrhoea, dysentery, arthritis, children's fevers, hypotriglyceridemic, haemorrhoids, vaginal discharge, rheumatism, and skin eruptions (4-9). This is due to the efficacy of *C. xanthorrhiza*'s pharmacology properties, which include anti-inflammatory, antibacterial, antioxidative, neuroprotective, nephroprotective, antitumor, and hepatoprotective activities (10-18). Previous scientific research revealed that the most abundant phytochemicals obtained from the *C. xanthorrhiza* rhizome were terpenoids and curcuminoids (19-21). As a result, the best medicinal activity was found in these two major groups of compounds (22). The rhizome of *C. xanthorrhiza* contributes to their main medicinal part, which contains many sesquiterpenoids and curcuminoids (19). As a result, market demand for *C. xanthorrhiza* rhizome is increasing over time.

3.5.4 Botanical Description

C. xanthorrhiza is a type of annual plant that can grow in clumps and has a pseudostem which mainly from 2-2.5 m in height. Each antecedent consists of few plants that were tillers as much 3 to 9 plants, and each one of the plant has 2-9 leaves. For its leaves, it have long and quite wide (50-55 cm long leaves with a width of approximately 18 cm) (Putri, 2013). *C. xanthorrhiza* flowers can continuously blooming throughout the year preferably coming out of the rhizome. The flower stalk consist of 3 cm in length and flower were arrange (inflorescentia) that might reaches to 1.5 cm. that one armpit which consist of 3-4 flowers. The flower stalk which is having slim and hairy with a length of 4-37 cm. The grain which has flower-shaped, that also elongated round which length can reach to 23 cm. *C. xanthorrhiza* that were consist of flowers that have many protective leaves which its length exceeded or it is proportional to the length of the flower crown. The flowers were bloom in the morning as for the afternoon, it will wilt (Dalimartha, 2000). The parent rhizome of *C. xanthorrhiza* is oval and round, like an egg, whereas the branch rhizome is elongated on the side part. Each plant has about 3-4 rhizome branches. *C. xanthorrhiza* has a fibrous root system with an irregular root length of about 2.5 cm (Putri, 2013).

3.5.5 Ethnomedicinal Uses

Since 1963, *C. xanthorrhiza* has been exported and used in Europe to treat dyspepsia, skin and liver illnesses, and infections. *C. xanthorrhiza* rhizome is commonly consumed fresh, as a decoction, steeping, powder, and as food. It is promoted in the industry as a semifinished product derived from the rhizome of *C. xanthorrhiza*, such as simplicial, starch, essential oil, and extract, and it is included in industrial products such as food and drink, cosmetics, instant powder, syrup, tablets, and capsule. Several scientific studies have demonstrated *C. xanthorrhiza*'s ethnomedicinal uses, which include treatment for skin disease, acne, and gastrointestinal problems such as dysentery, diarrhoea, haemorrhoid, constipation, and other digestive system problems related to its antimicrobial activity). Because of its anti-inflammatory properties, *C. xanthorrhiza* can aid in the treatment of arthritis (14, 52). It can also be used to treat some disorders, such

as metabolic syndrome (hypotriglyceridemia, which has been studied scientifically). Furthermore, *C. xanthorrhiza* has been shown in scientific studies to aid in the treatment of liver diseases. It also stated that the traditional efficacy of *C. xanthorrhiza* is commonly associated with its antimicrobial, antioxidant, and anti-inflammatory properties. Aside from that, the ability of *C. xanthorrhiza* to treat malaria has been evaluated preliminary by heme polymerization inhibition .



Figure 5.3 : the ethnobotanical properties

3.6 Phytochemical Properties of *C. xanthorrhiza* Roxb

3.6.1 Chemical Interaction of Curcumin with the Environmental Factors

The pure curcumin is in a crystalline form with a melting point around 183°C when exposed to room temperature. Besides, it is majorly covered with hydrophobic substance due to the non-polar regions in the aliphatic bridge, methyl groups, and aromatic rings (Gryniewicz & Slifirski, 2012). It is called deprotonated when it does have three hydroxyl groups, which are at sufficiently high pH values that giving it a negative charge. Therefore, the conditions of curcumin under acidic and neutral (where the hydroxyl groups are protonated), is a largely hydrophobic molecule with low water solubility, whereas as under alkaline condition (where the hydroxyl groups are deprotonated) it is formed as hydrophilic molecule with a relatively high-water solubility (Bernabe-Pineda *et al.*, 2004). For food products, the pH ranges from 2 to 8, which showed that the curcumin is a largely hydrophobic molecule which led to have low water solubility. In order to incorporated the curcumin into aqueous-based foods; it is commonly need to be dissolved in some form of hydrophobic substance, or else it will be in a crystalline form.

3.6.2 pH-induced colour changes

The changes of pH are depending on the color of curcumin solutions (where the three hydroxyl groups are protonated). From pH 2 to 7, all of the hydroxyl groups are protonated, and the colour of curcumin appears in golden yellow, which can be found in most foods. From pH 7 to 8.5, the enolic hydroxyl group becomes increasingly deprotonated, which led the curcumin to change to a more brownish-orangey colour. For the higher pH values, the colour of curcumin is more reddish due to the other two phenolic hydroxyl groups that become deprotonated. (Priyadarsini, 2014; Tonnesen *et al.*, 2002; Wang *et al.*, 1997). The UV-visible absorption spectrum can be used in as to measure the chemical state of curcumin under specific solution conditions (Priyadarsini, 2014). In conclusion, the curcumin chemically degrades which is under alkaline conditions, that can cause changes in its colour.

3.6.3 Photodegradation

Curcumin which in crystalline or solubilized form can undergoes the chemical reaction when it is exposed to light that develop colour fading (Priyadarsini, 2009; Wright *et al.*, 2013). Mostly, the crystalline form of curcumin is more stable to photodegradation as compared to solubilized form, due to the fraction of light waves that is able to penetrate into a clear solution. On a selected reaction products (e.g, vanillin and ferulic acid) that are reported to have some antioxidant and anticancer activities, but they are less vigorous than the curcumin molecule itself (Ogiwara *et al.*, 2002; Tai *et al.*, 2011; Gordon *et al.*, 2012).

3.6.4 Controlling Environmental Conditions

Curcumin has been shown to degrade more rapidly when exposed to light (Price & Buescher, 1996), high oxygen concentrations (Higaki *et al.*, 2001), elevated temperatures, and alkaline conditions (Kharat *et al.*, 2017). So, it is possible to improve its stability by controlling the environmental, solution, and/or packaging conditions. For example, the chemical stability of curcumin can be enhanced by incorporating it into acidic products (pH < 7), that are needed to be stored at low temperatures in the dark, (fruit juices, nutritional beverages, and dressings (Gryniewicz & Slifirski, 2012; Jain & Patil, 2015). On the other hand, it might be possible to keep out light and oxygen by using appropriate packaging materials and procedures, thereby further developing the stability of curcumin-based products.

4 Conclusion

The integration of curcumin as a material selection in smart and active packaging represents a significant advancement in the field of packaging innovation. By harnessing the natural properties of curcumin, such as its antimicrobial activity and antioxidant benefits, manufacturers can create packaging solutions that not only extend product shelf life and improve safety but also align with consumer preferences for sustainable materials. Synergistically combining curcumin with lipid-based antioxidants like carotenoids enhances

overall antioxidant capacity and extending the shelf life. As the industry continues to evolve in response to changing market dynamics and environmental challenges, the adoption of curcumin-based packaging stands as a testament to the potential of nature-inspired solutions to drive positive change. Besides, incorporating curcumin into active lipid films creates packaging materials with enhanced protective properties. Embracing such innovations not only enhances product quality and consumer satisfaction but also contributes to a more sustainable future for the packaging industry and the planet as a whole.

5 Publisher's Note

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