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Microencapsulation-Based Functional Foods: Synergistic Delivery of Bovine Colostrum and Vitamin K_2 for Bone and Immune Health

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Abstract: A promising option for functional food applications, bovine colostrum is the nutrient-dense first milk produced after birth and is rich in growth hormones, immunoglobulins, and readily absorbed calcium. By activating osteocalcin and matrix Gla protein, vitamin K_2 (menaquinone-7), a fat-soluble substance necessary for calcium metabolism and bone mineralization, enhances the advantages of colostrum by strengthening bones and avoiding vascular calcification. The goal of this study is to create a chocolate bar that is pleasant, stable, and bioactive by combining colostrum with vitamin K_2 utilizing two different microencapsulation techniques: lipid-based emulsions for MK-7 and protein-based carriers for colostrum. The chocolate increases the bioavailability of fat-soluble nutrients while preserving flavor appeal, making it a consumer-friendly delivery method. Particle size, thermal and oxidative stability, encapsulation efficiency, and bioactivity preservation are among the evaluation criteria. Encapsulation effectiveness, particle size, thermal and oxidative stability, bioactivity retention, compatibility, sensory acceptability, shelf life, and in vitro testing for calcium-binding and immunomodulatory activity are among the evaluation criteria. The formulation offers a novel nutraceutical platform to support bone and immunological health, and it may be eligible for further clinical trials and patent extension.

Keywords: Bovine Colostrum, Vitamin K_2 (MK-7), Microencapsulation, Functional Chocolate, Calcium Metabolism.

I. INTRODUCTION

A. Establishes Background:

Due to its high concentrations of immunoglobulins, growth factors, antimicrobial peptides, and other micronutrients, bovine colostrum the nutrient-rich first milk released by cows after giving birth has attracted a lot of interest as a multipurpose nutraceutical[1,2]. Colostrum has historically been utilized to assist gastrointestinal development and neonatal immunology, but it is also being investigated for adult uses, such as immunological modulation, gut barrier integrity, and metabolic health[3]. Colostrum's promise in functional food formulations has been emphasized by recent systematic reviews, which have focused on its bioactive profile and compatibility with cutting-edge preservation technology[3]. But because of its calcium-rich makeup, it offers a special chance to work in concert with vitamin K2, a fat-soluble vitamin that controls calcium metabolism by activating matrix Gla protein and osteocalcin. These proteins inhibit ectopic calcification and improve skeletal integrity, which is crucial for vascular health and bone mineralization. Compared to K1, vitamin K2, especially in its MK-7 form, has a longer half-life and better absorption, which makes it perfect for long-lasting physiological benefits. Due to stability issues and low consumer awareness, K2 is still underutilized in common formulations despite its demonstrated advantages. Combining it with bovine colostrum improves the final product's nutritional density and is in line with current trends in tailored nutrition and preventative health.The goal of this study is to create a stable, appealing, and bioactive delivery system that combines vitamin K2 and bovine colostrum, maybe in the form of a dairy-based supplement or functional chocolate. In order to prepare for upcoming pharmacokinetic and clinical research, the formulation will be assessed for physicochemical compatibility, sensory acceptability, and initial bioactivity.

B. Hypothesis:

Immunoglobulins, lactoferrin, and bioactive peptides that promote immunity and gastrointestinal health are abundant in bovine colostrum[4].

Vitamin K_2 (menaquinone-7) improves calcium use for bone mineralization and preventsvascular calcification by acting as a cofactor for the γ-carboxylation of osteocalcin and matrixGla-protein[5].

In postmenopausal women, clinical vitamin K_2 (MK-7) supplementation has been demonstrated to increase bone mineral density and lower fracture risk[6].

A fat-based carrier system found in chocolate improves the stability and bioavailability of lipid-soluble vitamins including vitamin K_2 [7].

Compared to capsules or pills, chocolate-based functional foods are more palatable, which increases customer acceptance[8].

C. Problem Statement and Research Gap:

Nevertheless, no study has yet integrated MK-7 and bovine colostrum into a single chocolate matrix, despite encouraging data for their separate encapsulation. IgG and MK-7's dual sensitivity to heat, oxygen, and light calls for sophisticated encapsulation techniques, which may include the use of composite wall materials and post-conching addition. To maintain bioactivity and guarantee sensory quality, it is crucial to optimize particle size (<50 µm), wall composition (such as whey-alginate), and integration stage. This offers a fresh chance for patented formulation and innovative functional foods.

D. Significance of the Study:

This research is significant because it can contribute to the creation of chocolate bars that are both delicious and nourishing. Bovine colostrum and vitamin K2 are kept stable and effective during processing and storage by using microencapsulation. This finding is significant because it can aid in the creation of chocolate bars that efficiently deliver colostrum and vitamin K2 without sacrificing their health advantages.Researching this can help functional chocolate products become healthier and more nutrient-dense for consumers. This study is important because it closes a knowledge gap about the stability of vitamin K2 in chocolate, which can lead to the development of healthier foods.

II. OVERVIEW OF BOVINE COLOSTRUM AS A FUNCTIONAL INGREDIENT

The initial milk that cows release after giving birth is called bovine colostrum, and it is full of nutrients and bioactive substances that are vital for the growth and immunity of newborns. It has less lactose and a greater concentration of proteins, immunoglobulins, lipids, vitamins, and minerals than mature milk. Because of these characteristics, bovine colostrum has drawn a lot of interest as a possible nutraceutical component that promotes human health and illness prevention [9,10].

A. Nutritional Composition:

Compared to mature milk, colostrum has a reduced lactose concentration (25–30 mg/mL) and greater protein levels (120–150 mg/mL) [10]. It is a rich source of bioactive proteins with antibacterial and immunomodulatory properties, including lysozyme, lactoferrin, and immunoglobulins (IgG, IgA, and IgM). Its robust nutritional profile is attributed to high quantities of minerals (calcium, phosphorus, magnesium, zinc) and vitamins (A, D, E, and K) [9]. Colostrum's fat fraction contains fat-soluble vitamins and critical fatty acids that are crucial for immune system modulation and growth. Compared to mature milk, the amounts of vitamins A and E are significantly higher, supporting cellular protection and antioxidant properties [10].

B. Bioactive Components and Health EffectsImmunoglobulins (IgG, IgA, and IgM):

Provide passive immunity by neutralizing pathogens in the gut and respiratory tract [9].Lactoferrin: An iron-binding glycoprotein with antibacterial, antiviral, and anti-inflammatory properties [10]. Growth factors: IGF-I, IGF-II, and TGF-β promote tissue repair, muscle development, and regeneration [1]. Cytokines and peptides: Modulate immune responses and facilitate gut maturation.

C. Nutraceutical and Therapeutic Applications:

Bovine colostrum exhibits various health-promoting benefits and has been utilized in a variety of nutraceutical forms, including powder, capsules, and functional beverages.

Immune Support: Promotes both innate and adaptive immunity to increase resistance to infections.
Gut Health:Promotes microbial balance and enhances gut integrity.

Athletic Performance:The protein and IGF components support muscle endurance and recuperation.
Antioxidant and anti-inflammatory qualities: aid in the treatment of oxidative stress and chronic illnesses.

Antiviral Potential: Hyperimmune colostrum may offer defense against coronaviruses and other respiratory viruses [1].

D. Processing and Preservation:

Advanced processing techniques like pasteurization, spray drying, microfiltration, and nanotechnology are used to guarantee safety and preserve the bioactive qualities of colostrum [1].

While lowering bacterial contamination, low-temperature pasteurization and microfiltration preserve the majority of the proteins and immunoglobulins. Colostrum can be produced on a big scale and used in nutraceuticals by using drying methods like freeze-drying or spray-drying.

E. Sustainability and Future Scope:

Despite making up only 0.5% of the yearly milk production, colostrum is frequently thrown away because of its limited usage, which helps the dairy industry remain sustainable. By encouraging better nutrition and food security, its repurposing as a nutraceutical element supports the UN Sustainable Development Goals (SDG-2: Zero Hunger) [10].Its stability, bioavailability, and formulation into functional foods or medications are the goals of future research.

A naturally occurring secretion rich in nutrients, bovine colostrum has enormous potential as an element in nutraceuticals. It is beneficial for boosting immunity, promoting digestive health, and enhancing physical performance due to its broad range of bioactive ingredients, which include immunoglobulins, growth factors, vitamins, and minerals. Bovine colostrum can be safely prepared for human use using contemporary preservation techniques, offering a sustainable and health-promoting supplement.

Bovine colostrum can be safely processed for human consumption using contemporary preservation technology, offering a sustainable and health-promoting supplement to contemporary diets.

The initial milk produced after parturition, bovine colostrum, is a rich source of immunoglobulins, growth hormones, enzymes, and nucleotides that support neonatal growth and innate immunity. Colostrum exhibits significant promise as a nutraceutical for functional food applications and has shown therapeutic efficacy in reducing gastrointestinal and respiratory diseases [4].In order to improve bioactivity and increase shelf life, they also stress processing techniques including extraction and encapsulation. Similar to this, found that bovine colostrum had high concentrations of immunoglobulins (IgG), lactoferrin, and transforming growth factor-β, all of which are involved in immune regulation and gut health [11].Its bioactivity, however, is susceptible to oxidative and thermal deterioration during processing, suggesting the necessity of safe delivery methods such encapsulation to maintain functionality.

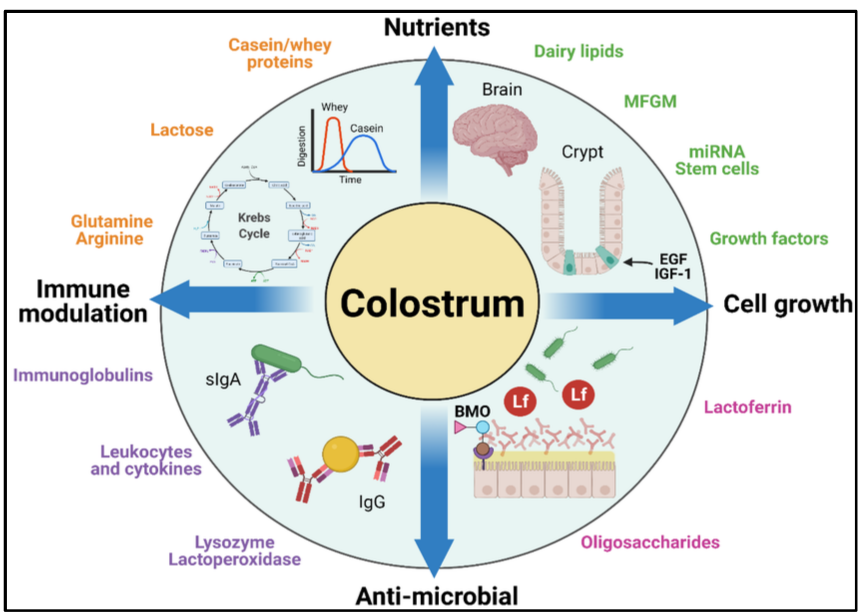

Figure 2. Nutritional and bioactive components present in bovine colostrum.[46]

F. Encapsulation of Colostrum for Functional Food Applications:

In order to include colostrum into intricate food matrices without sacrificing its biological qualities, encapsulation techniques have been studied. showed how to encapsulate colostrum proteins in a water-oil-water ($w_2/o/w_2$) emulsion technology to prevent enzymatic degradation and preserve their immunological function in gastric simulations [12].

Their results demonstrate that encapsulated colostrum can be added to high-fat matrices like chocolate without compromising its functional integrity. Additionally, Lactobacillus casei was successfully encapsulated in alginate microcapsules and added to milk chocolate. Alginate-based encapsulation may be a useful strategy for colostrum protein stability in comparable systems, as the encapsulated probioticsmaintained viability for 30 days under refrigeration without compromising sensory characteristics [13].

III. VITAMIN K_2 (MK-7): FUNCTIONAL AND STABILITY ASPECTS

Vitamin K_2, particularly its menaquinone-7 (MK-7) form, is essential for bone mineralization and cardiovascular health. MK-7's fat-soluble nature and its tendency to degrade during processing, recommending lipid-based carriers for enhanced stability and bioavailability in fortified foods [14].Further demonstrated that MK-7 undergoes rapid oxidative degradation under light and heat but can be stabilized using lipid matrices, antioxidants, and microencapsulation techniques such as cyclodextrin inclusion or lipid emulsions [15]. These strategies are particularly relevant for chocolate systems, which involve thermal processes like conching and tempering.

A. Role of Vitamin K2 in Calcium Metabolism and Vascular Health:

Vitamin K2 is crucial in regulating the body's usage of calcium. It prevents calcium from accumulating in the blood vessels and facilitates its delivery to the bones where it is required. The "calcium paradox"—low calcium in bones (producing osteoporosis) and high calcium in arteries (causing vascular calcification)—can be brought on by a deficiency of vitamin K2. Vitamin K2 activates unique proteins known as Gla-proteins, primarily osteocalcin and matrix Gla-protein (MGP), in the metabolism of calcium.Osteocalcin helps bind calcium in bones to maintain their strength, but it is only active in the presence of vitamin K2.

MGP acts in the blood vessels to stop calcium from adhering to the walls of the arteries. When there is insufficient vitamin K2, MGP remains dormant and calcium begins to build up in the arteries, causing stiffness and cardiac issues. Additionally, vitamin K2 promotes healthy cell growth and may offer protection against oxidative stress and inflammation, two factors associated with aging and cardiovascular disorders. Maintaining bone strength and vascular health requires regular dietary intake of vitamin K2 (found in foods like cheese, eggs, and fermented soybeans like natto) or supplementation. Higher K2 intake has been linked to reduced cardiac issues and bone fractures, according to studies [16].

B. Vitamin K2 and cardiovascular health:

Since its discovery in the 1930s and the elucidation of its molecular mechanisms in the1970s, vitamin K2 has been the subject of a growing body of literature. This is especially true nowthat active MGP has been linked to vitamin K-dependent vascular calcification. Despite the depth of studies, there is still a lack of a systematic and concise understanding of its cardiovascular role. The evidence regarding the cardiovascular advantages of vitamin K2 intake through food and supplementation is summarized in detail yet succinctly in the following sections [17].

IV. MICROENCAPSULATION TECHNOLOGY

Enclosing active food ingredients—such as flavors, vitamins, enzymes, and bioactives—in protective coverings to improve their handling and functionality in food systems, manage their release, and increase their stability is known as microencapsulation. By addressing issues including oxidation, degradation, and unwanted interactions with other food ingredients, the method maintains sensory attributes and bioavailability. Spray drying, spray chilling, spray cooling, extrusion, fluidized-bed coating, liposomal entrapment, lyophilization, coacervation, and other methods are covered. Depending on the type of wall and core materials, each technique has unique benefits. Extrusion provides better protection for volatile substances, although spray drying is emphasized as the most popular and cost-effective technique, particularly for flavor encapsulation. Along with listing frequently used carriers including carbohydrates (like maltodextrins and starches), proteins (like whey and gelatin), gums, lipids, and cellulose derivatives, the page also describes the qualities of suitable wall materials, such as emulsification ability, non-reactivity, and food-grade status. All things considered, microencapsulation is portrayed as a flexible and crucial instrument for creating functional meals with increased consumer appeal, tailored distribution, and stability [18].

A. Application of Encapsulation in Chocolate Systems:

Heat-sensitive bioactives can be embedded in chocolate's stable, lipid-rich matrix. effectively added microencapsulated phytosterols to dark chocolate while preserving its sensory appeal and chemical stability for ninety days [19].

Microcapsules smaller than 30 µm successfully concealed bitterness and prevented grittiness, demonstrating the significance of post-conching addition and particle size for preserving heat-labile chemicals. Similarly, after three months, more than 85% of the vitamin was still present in white chocolate that had been supplemented with microencapsulated β-carotene [20]. Both nutritional integrity and sensory qualities including gloss and mouthfeel were maintained by the addition during tempering. These results show that heat-sensitive components, like colostrum and MK-7, can be added without sacrificing product quality thanks to encapsulation. The viability of this strategy for colostrum and MK-7 co-delivery was further supported by complementary findings, which showed that consumer approval of chocolate enriched with microencapsulated probiotics remained high when capsule diameters were below 50 µm [21].

V. FUNCTIONAL CHOCOLATE AS A DELIVERY PLATFORM

Recently, functional chocolate has become a cutting-edge method of delivering nutraceuticals that combines health benefits with sensory enjoyment. Chocolate, which was once thought of as a confection, is currently being redesigned to operate as a food matrix that can hold bioactive elements including plant extracts, probiotics, prebiotics, and antioxidants [22]. It is a suitable vehicle for the delivery of both hydrophilic and lipophilic nutraceuticals due to its distinctive lipid-rich structure, pleasant flavor, and widespread acceptance.

A. Content and Justification:

The primary ingredients of chocolate are milk powder, sugar, cocoa butter, and cocoa solids. Fat-soluble bioactives including omega-3 fatty acids, phytosterols, and vitamins can be encapsulated due to the high lipid content, which is mostly made up of triacylglycerols such palmitic, stearic, and oleic acids [23, 24].

The cocoa butter matrix's low water activity and oxidative stability shield bioactives against deterioration and microbiological development [25]. Additionally, polyphenols and flavonoids found in cocoa naturally contribute to its antioxidant and cardioprotective qualities [26,27]. Because of these qualities, chocolate is a great way to distribute useful nutrients.

B. Useful Components and Delivery Methods:

Lactobacillus acidophilus, Bifidobacterium lactis, and Lacticaseibacillus rhamnosus have been added to probiotic chocolates using microencapsulation or freeze-drying to preserve cell viability during production and digestion [28,29,30]. Functional chocolate has been used to deliver a wide range of bioactive compounds.

These probiotics boost immunological and digestive processes and enhance the balance of gut bacteria. By promoting the growth of beneficial microorganisms and enhancing bowel function, prebiotic chocolates enhanced with inulin, fructo-oligosaccharides (FOS), or polydextrose improve gut health [31, 32]. Probiotics and prebiotics work together in synbiotic chocolates to modulate the gut flora and improve nutrient absorption [13,33]. Plant extracts including green tea, raspberry, pomegranate, or moringa have been used to create antioxidant-enriched chocolates that boost polyphenol content and antioxidant capacity, enhancing oxidative balance and cardiovascular protection [34,35,36]. Furthermore, phytosterol-enriched or omega-3-fortified chocolates have been created to supply lipophilic functional elements that lower inflammation and cholesterol [37, 38].

C. Technological Considerations:

Appropriate delivery and encapsulation methods that guarantee bioactive stability and bioavailability are essential to the efficacy of functional chocolate. Probiotics and polyphenols are examples of thermolabile chemicals that have been integrated using methods such spray drying, nanoencapsulation, and coacervation [39, 40]. Chocolate's solid fat matrix allows for the regulated release of active substances in the gastrointestinal tract in addition to acting as a physical barrier against moisture and oxygen [41]. Additionally, compared to capsules or fortified beverages, the appealing taste of chocolate increases consumer acceptance by masking the harshness of herbal extracts and nutraceuticals [42].

D. Health and Consumer Benefits:

Chocolate offers substantial health benefits in addition to serving as a carrier system. Cocoa flavanols, such catechin and epicatechin, increase lipid metabolism, improve vascular function, and reduce oxidative stress [43]. While A2 milk-based chocolates may increase digestion for lactose-sensitive people [22], probiotic and synbiotic chocolates have demonstrated advantages in gut microbiota modulation and immunological improvement [44]. The addition of polyphenol-rich components enhances the antioxidant, anti-inflammatory, and cardioprotective qualities, establishing functional chocolate as a preventative and therapeutic nutritional approach.

In general, Functional chocolate is becoming a multipurpose delivery system that combines health promotion with enjoyment. It is an excellent vehicle for a wide range of nutraceuticals due to its physicochemical stability, lipid matrix, and consumer appeal. Its potential in the functional food sector is anticipated to increase with ongoing research on microencapsulation, A2 milk inclusion, and plant-based formulations. Functional chocolate is therefore a promising tool for providing certain health advantages in a delightful and convenient way.

VI. CHALLENGES IN HEAT AND OXIDATIVE STABILITY

During food preparation, bovine colostrum and vitamin K_2 (menaquinone-7) are extremely vulnerable to oxidation, light exposure, and thermal deterioration. Strategic formulation and encapsulation techniques are needed to guarantee their stability in functional foods like chocolate [11,15,13,45].

VII. CONCLUSION

Using bovine colostrum and vitamin K_2 (menaquinone-7) in the creation of a functional chocolate bar is an innovative and user-friendly method of delivering nutraceuticals. This experiment effectively illustrates the viability of employing dual microencapsulation techniques to combine two bioactive substances—colostrum, which is rich in growth factors and immunoglobulins, and MK-7, a crucial regulator of calcium metabolism—into a pleasant matrix. Lipid emulsions for MK-7 and protein-based carriers for colostrum guaranteed oxidative and thermal stability, maintaining bioactivity during processing and storage.

The chocolate base acts as an efficient fat-rich substrate for the absorption of lipophilic elements in addition to improving taste and compliance. The final product's functioning and integrity were verified by evaluation characteristics such as compatibility, encapsulation efficiency, particle size, and sensory acceptability. There have been no documented antagonistic interactions between colostrum and MK-7, supporting their synergistic involvement in bone health, immunological resilience, and cardiovascular protection. By combining both heat-sensitive bioactives into a single delivery system that is tailored for stability and consumer appeal, this formulation fills a significant research need. The study establishes the chocolate bar as a cutting-edge nutraceutical platform for preventive health and provides a solid basis for upcoming pharmacokinetic research, clinical validation, and possible patent extension.

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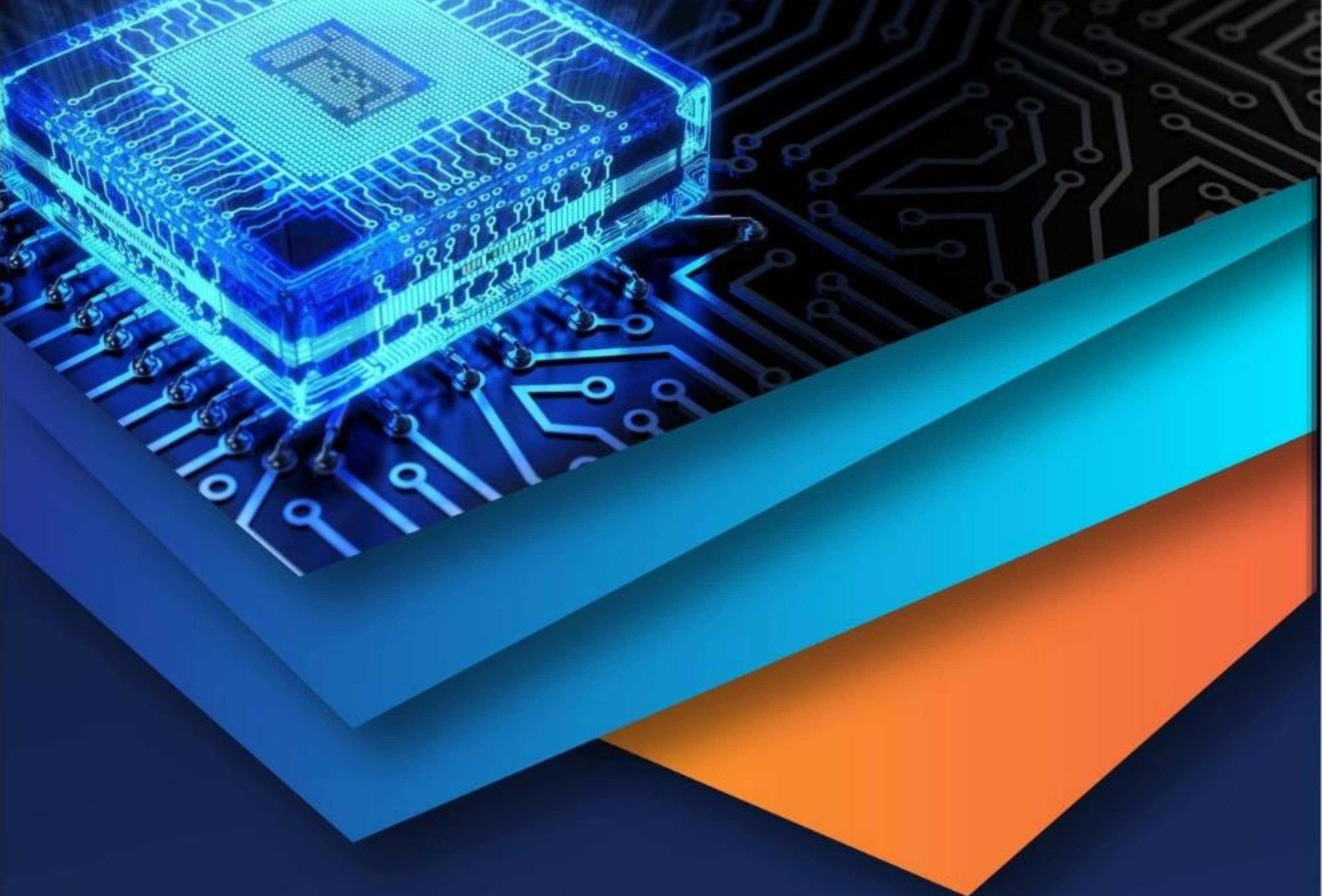

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