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RESEARCH ARTICLE

Unraveling Curcumin's Molecular Impact on Human Health

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ABSTRACT: Turmeric (*Curcuma longa*), a widely used spice with a long history of medicinal and cultural significance, is renowned for its vibrant yellow color and distinct flavor, attributed to curcumin, a polyphenol with diverse biological activities. This review delves into the molecular mechanisms of curcumin, exploring its structure, extraction methods, bioavailability, and diverse pharmacological effects. Curcumin's chemical structure, characterized by conjugated double bonds and phenolic hydroxyl groups, contributes to its potent antioxidant and anti-inflammatory properties. Various extraction methods, including solvent extraction and supercritical fluid extraction, have been employed to isolate curcumin from turmeric rhizomes, each with advantages and limitations regarding yield and purity. Despite its low bioavailability due to poor water solubility, curcumin has demonstrated potential pharmacological effects, such as anti-inflammatory, antioxidant, and neuroprotective properties. Its interactions with various molecular targets mediate these effects, modulating signaling pathways involved in inflammation, oxidative stress, cell proliferation, and apoptosis. This review also addresses the challenges associated with curcumin's bioavailability and highlights ongoing research efforts to enhance its therapeutic potential through innovative delivery systems and formulations. Understanding the molecular mechanisms underlying curcumin's actions is crucial for developing effective therapeutic applications and unlocking its full potential for improving human health.

KEYWORDS: Biochemistry, Structural Biochemistry, Curcumin, Molecular Mechanisms, Anti-inflammatory.

Introduction

Turmeric, also known as *Curcuma longa*, or "the golden spice" due to its distinct and bright orange color, is a plant that is a part of the family Zingiberaceae. Turmeric is an herb that grows upright from the ground to a medium height, and the plant itself grows white flowers from the buds. However, the primary use of turmeric is harvesting its rhizomes, which grow into the ground as roots. The rhizomes of the turmeric plant are often yellow-brown and branch off into several nodes that stem from the main 'mother rhizome' at the base of the plant. These are usually harvested in the spring months of March-April, when the turmeric plant is at its peak maturity, using a spade. After the turmeric plant is harvested, it is taken to a facility where it gets steamed, boiled, and then dried into powder form, which is commercially used most often as a spice in Indian dishes.

Turmeric has been used in medicine for over 6,000 years, originating in India and spreading globally as a remedy for various ailments. It was first named by Marco Polo in 1280 due to its similarity to a saffron spice.[1] Turmeric had and has great significance in India, where turmeric has great cultural importance as well, but this notion of the importance of turmeric has spread to the world. The information about the benefits of turmeric became popular around the 8th century in Africa and China. The main reason for the quick and extensive spread of turmeric's influence is its reputation as a 'spice of life,' often used as a traditional home remedy for treating common illnesses and disorders. A few examples of disorders that turmeric is well-known to treat are anorexia, cough, wounds, relief of indigestion, scorpion pain stings, liver obstructions, ulcers, and numerous other health complications in countless cultures and countries.[2] In modern times, turmeric is cultivated in several regions worldwide, including India, China, Thailand, Bangladesh, Malaysia, Indonesia, and certain tropical regions. Turmeric is best grown in regions with a humid climate, with year-round rainfall to develop and mature fully.

Apart from the historical significance of the turmeric plant, it also has cultural and religious importance, primarily in India, where the plant originated. In the beginnings of India's culture, turmeric was used during ceremonies to protect the face during the worship of the sun.[3] As time passed, turmeric grew more and more important in religious ceremonies, with many believing that turmeric was a representation of the sun due to its bright orange color. In modern-day India, turmeric is used in marriage rituals. This review explores curcumin's molecular mechanisms and assesses its potential as a complementary therapeutic agent.

Discussion

Section 1: Composition and Molecular Structure:

Curcumin, also known as diferuloylmethane, is a critical molecule in turmeric. Curcumin provides most of turmeric's health benefits and gleaming color. It is a bright yellow crystalline polyphenol, a substance in many vegetables, and is the main reason for its extensive nutritional and health results. Polyphenols can protect the body's tissues and alleviate some cancers and inflammation, one of turmeric's main properties. Polyphenols can provide these incredible benefits because of their ability to reduce the amount of reactive oxygen species in the body, which are the primary cause of several diseases.[1] Due to curcumin's ability to provide ample health advantages, its structure is compared with other molecules within turmeric. The overall composition of the turmeric spice is that it contains 5.1% fat, 6.3% protein, 69.4% carbohydrates, 3.5% minerals, and 13.1% moisture.

Additionally, curcumin is deemed a 'curcuminoid,' a term used to label the numerous molecules in turmeric.[2] Curcumin's melting point is 183 °C. Its molecular formula is $C_{21}H_{20}O_6$. The most abundant curcuminoids within turmeric are curcumin, demethoxycurcumin, and bisdemethoxycurcumin, although other analogs of curcuminoids may exist within turmeric. About 2-9% of turmeric is comprised of curcuminoids, and of this percentage, the percentages of these specific molecules in turmeric are approximately 80% curcumin, 17% demethoxycurcumin, and 3% bisdemethoxycurcumin. Curcumin is the most potent molecule in turmeric due to its chemical structure compared to other curcuminoids. Curcuminoids are regarded as entirely safe and nutritional compounds, and they were approved by the World Health Organization and the Food and Drug Administration through experimentation, approving the compound to be used in various forms such as culinary, agricultural, and, most notably, medicinal use. An important feature of curcuminoids is that they often provide more potent effects when mixed rather than when extracted and used independently.[3] This use of the spice has been shown in turmeric's extensively studied pharmaceutical effects, including anti-viral, anti-microbial, anti-inflammatory, and anti-carcinogenic. Furthermore, a critical characteristic of curcumin that is notable in providing results that will be later elaborated on is that it is an insoluble molecule in water. This is especially true at neutral and acidic pHs due to how the structure of the curcumin molecule changes based on the pH of the solution and, therefore, can affect the nonpolar bonds within curcumin, affecting its solubility. Data taken to determine the solubility of curcuminoids in water is shown as follows. Three acidity constants were measured for curcuminoids: $pKa_1 = 8.38 \pm 0.04$, $pKa_2 = 9.88 \pm 0.02$, and $pKa_3 = 10.51 \pm 0.01$.[4] The data shows a high pKa for curcuminoids compared to most substances, indicating little ability to be soluble in water and dissolve thoroughly. Thus, curcumin is hydrophobic and soluble in acetone, ethanol, and dimethyl sulfoxide. This information is essential in the extraction of curcuminoids from turmeric because using the solubilities of compounds in extraction allows scientists to isolate specific molecules within turmeric. Compounds like hexane, acetone, methanol, isopropanol, and ethyl acetate are commonly used as solvents for their ability to dissolve and interact with molecules of several curcuminoids.

Curcumin's molecular structure and composition are the main reasons for its ability to provide benefits and uses, which will be described in detail later.[5] Research has shown that the composition of metabolites in curcumin, compared with other compounds like curcumin, can improve the curcumin molecule's molecular stability. Metabolites are compounds essential in the human body's processes. Curcumin's slight differences in its composition of metabolites yield different biological effects and overall chemical activity in the body's mechanisms.[6] Additionally, research on curcumin's chemical structure has demonstrated that turmeric's therapeutic properties can be attributed to the electron-donating groups on the curcumin molecule. This component of the curcumin molecule allows it to scavenge free radicals within the body and remove the excessive ones. A free radical is a compound with an unpaired valence electron in its molecular structure; free radicals are dangerous because they can alter key metabolites within the body and trigger numerous diseases. This property of the curcumin molecule yields most of turmeric's health benefits. It opens more opportunities for turmeric spice for novel applications such as agriculture and cosmetics, which will be discussed later.

Section 2: Extraction Methods:

Two different branches of extraction methods have been commonly used in studying curcumin, turmeric, and other curcuminoids. These branches are the methodologies used in the past, also known as conventional routes, along with the modern technologies being developed and used today, known as modern routes.[7] Extraction of molecules from an organic compound requires that two immiscible or indissolvable liquids are separated through various means based on their solubilities. In the case of turmeric, its dried rhizomes (roots) are harvested and used for testing. Scientists have thoroughly researched methods to extract key curcuminoids present in turmeric due to the extremely high potential of curcuminoids to be used in commercial products. Traditional methods have shown low yield, high environmental effects, and high economic cost, so scientists are working to produce more efficient, environmentally friendly, and accurate extraction methods. This is necessary because, without sustainable methods of extraction of the active molecules in turmeric, scientists cannot explore the boundless uses of the curcuminoids within it. This has resulted in numerous possibilities of extraction developed over the past years, with differing advantages and disadvantages to using the beneficial substances found within turmeric. Since multiple methods of extraction have been utilized in past years, this review will cover the novel techniques that have arisen recently, with an overview of conventionally used extraction methods. This includes hydro-distillation, supercritical fluid-based extraction, and a combination of microwave extraction and response surface methods.

One extraction method utilized in the past to isolate curcuminoids from turmeric was solvent extraction using organic solvents. This conventional method of extraction has been used most often due to its simplicity; however, with it comes far more disadvantages than modern methods. This traditional extraction method, hydro-distillation, is used to remove bioactive compounds within organic substances. It utilizes hot water and steam as solvents to extract compounds from plant tissue. A key feature of this procedure is that it can bypass the step of extraction used by other methods, where one must separate the nonpolar solvent and the extract because the bioactive compound that is trying to be isolated is already separated through a vapor condenser device. The procedure begins with the turmeric rhizome being placed in a water tub to be boiled; a large majority of compounds to be extracted using this method have high boiling points, which creates an advantage to this method because essential oils within the compound will remain intact. The hot water and steam used in hydro-distillation extract

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compounds from its organic plant, utilizing chemical processes such as hydrolysis and decomposition, which aid in this process. After it is boiled, the liquid produced demonstrates a separation between the essential oils of turmeric and the turmeric plant itself by injecting steam within the plant material to enhance this. As the substance cools, the mixture condenses and is brought to a separator, allowing the essential oils and the organic compound to separate automatically. Some disadvantages to this method of separation include that it takes copious amounts of time for the essential oils to separate from their organic compound, and overall, it has shown inconsistent and low amounts of products.

Supercritical fluid-based extraction is a recent method of extracting curcuminoids present in turmeric.[8] This is where a fluid known as a 'supercritical fluid' is utilized at a temperature and pressure above its critical point, allowing it to be used commercially to extract substances from organic food products, such as turmeric. An overview of the procedure required to conduct this extraction method is using a supercritical fluid, commonly CO_2, which acts as a non-polar solvent because it is a supercritical fluid. The supercritical fluid cannot create intermolecular forces between molecules due to the high kinetic energy the particles of the substances are undergoing due to the substance being at its critical point. This then allows the fluid to act as a non-polar solvent, allowing the substances to be extracted through the methods of separation of the two immiscible compounds, in this case being the supercritical fluid and the curcuminoids within turmeric, based on their solubilities as described previously. A study by Baumann et al. utilizing this method demonstrated suitable results by using supercritical CO_2 modified by 10% ethanol to extract several curcuminoids in turmeric. The quantitative results are that by use of this supercritical fluid method, there was about 1.8-2.5% of extractable curcumin content from turmeric; this experiment used turmeric plants from 3 separate locations to determine the efficacy of the supercritical fluid extraction method for all kinds of turmeric. Overall, this extraction method resulted in reasonable yields and low amounts of impurities in the products. Additionally, its procedures have proved to be environmentally friendly because of the little residue produced, which is a feature, unlike several other extraction methods. It is also economically friendly due to CO_2 being inexpensive to use. However, this process has shown some inconsistencies and difficulties on a large scale. This is due to the high pressures required to achieve a supercritical fluid at these large scales, resulting in an unstable system.[9] Furthermore, if the supercritical fluid were to undergo minuscule changes in its temperature or pressure, the procedure would be inconclusive in extracting curcuminoids from turmeric due to the critical conditions of the disturbed supercritical fluid.

The final and most promising extraction method, with the least error and highest yield compared to other extraction methods, is described as a combination of microwave extraction methods and response surface methods.[10] Response surface methods is a statistics concept where two or more methods in the extraction process are optimized until the desired outcome is reached. The RSM method can predict the experiment's outcome, equate for the desired outcome, and design an experiment; RSM can model the interactions using 3-D modeling techniques. RSM is utilized not only in extracting active compounds from an organic substance but also for data analysis, experimental design, or product design. This extraction procedure takes advantage of the positive results found in previously described extraction methods and reduces their limitations through the optimization technology of RSM. The process begins with thoroughly washing the turmeric rhizome to remove impurities that could affect the results. Then, the rhizome is placed in a microwave oven, which provides a heat source. The procedure then follows the same as the hydro-distillation process, separating the essential oils of turmeric from its organic plant material. To optimize the exp experiment with RSM, three factors were considered when considering what could affect the yield of the procedure. There is the ratio of water and rhizome in turmeric, extraction time, which, in other experiments, has shown an increase in yield as extraction time increases, and microwave energy. Complex software was used to predict the most optimal adjustments to these factors for the most optimal experimental conditions. The results of 20 experiments utilizing this technique were a %0.95 yield with 2.99:1 mL/g at the extraction time of 102.43 min and microwave power of 456.60 W. This procedure demonstrated that the utilization of this technique in combination with other extraction methods results in higher quality and quantity of essential oils and curcuminoid compounds extracted from the plant material rhizome of turmeric. This data allows scientists to improve their extraction techniques, consequently providing higher-quality curcuminoid molecules for their extensive biological properties in commercial products. Consequently, this will increase the potency of the curcuminoid in whichever product they are utilized in, which would improve the already existing benefits the molecules deliver.

Section 3.1: Curcumin and Disease: A Deeper Dive into Molecular Interactions:

Curcumin's potential to regulate many diseases is due to the regulation of inflammatory signaling created by the body. Curcumin has also been shown to contribute to regulating type II diabetes since it has been demonstrated through several tests to overcome insulin resistance.[11] Curcumin's ability to resist cardiovascular diseases is mainly because of its ability to regulate platelet aggregation in a specific section/area of the body; the suppression of inflammatory substances within the body is partly the reason for the molecule's ability to relieve Alzheimer's disease symptoms.[12]

Section 3.2: Anti-inflammatory:

Applying the extraction methods previously described allows curcumin within turmeric to be utilized for its apparent health benefits. One of the many medicinal properties of turmeric is its anti-inflammatory qualities, which are used in modern and traditional medicine worldwide. Studies on the anti-inflammatory properties of curcuminoids have yielded results with potential.[13] The results of a study by Ramsewk *et al.* have shown cytotoxic (how toxic a substance is against cells) activity against leukemia, colon cancer, CNS melanoma, renal and breast cancer. Curcuminoids have demonstrated combat

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ive activity against inflammatory-related symptoms of these diseases. These studies demonstrate the essential properties of turmeric extract and its promising use in the medicinal field as a natural alternative to existing drugs to prevent inflammation. One experiment to test the effectiveness of curcuminoids as anti-inflammatory compounds for the body's well-being is through curcumin in mice with edema (swelling of the feet).[14] Mice given 50-200 mg/kg doses achieved a 50% reduction in edema. In an oral experiment to determine the use of curcumin and turmeric in dentistry, mice were tested with a dose of 30x higher curcuminoids before arthritis induction. This resulted in a reduction of joint inflammation by around 48%.

Another approach used to test the anti-inflammatory effects of the turmeric rhizome was conducted and analyzed. This process utilized several cells (HL-60) found within the human body, specifically cell linings, to test curcuminoids' effect on them once they are affected by *E. coli*. This experimentation demonstrated that curcuminoids could inhibit the production of TNF-α and PGE2. TNF-α is a compound responsible for cell necrosis and apoptosis, the leading cause of inflammation and cell death in the body. PGE2 is a compound in the body that is the primary inducer and initiator of inflammation and auto-immune diseases.[12] Specific data to support this claim of the efficacy of curcuminoids on inflammation-related compounds is that The IC50 value for inhibition was 15.2 mg/ml for TNF-α and 0.92 mg/ml for PGE2. An IC50 value indicates how much drug or substance, such as curcuminoids, is required to inhibit biological processes in half, inhibiting inflammatory-related substances within the body, TNF-α, and PGE2. Curcumin demonstrated the highest inhibition of these compounds within the body compared to demethoxycurcumin and bisdemethoxycurcumin. However, all three were effective. One distinction to note is that the inhibition of the PGE2 compounds required far less concentration of curcuminoids to inhibit in comparison with the TNF-α compounds.[15] The experiment results were positive and expected because they demonstrated how beneficial curcuminoids are in preventing inflammation within the body, specifically those of the compounds described.

Additionally, a commonality of the properties of turmeric mentioned by several researchers is that the active molecules within turmeric have the innate ability to inhibit COX-2, which stands for cyclooxygenase 2.[16] This is an enzyme in the human body that is involved in the production of substances that are responsible for inflammation, such as PGE2 and TNF-α previously mentioned, because of external stimuli that the body is exposed to. A continuation of the previous study on PGE2 and TNF-α, which describes the effects of curcumin at different concentrations on the inhibition of COX-2, showed promising results. Data shows that when curcumin was at concentrations as low as 0.5 mg/ml, it decreased COX-2 expression in cells by more than 50%. However, when the procedure was repeated using curcumin at a concentration of 10 mg/ml, no significant changes in the expression of COX-2 in cells were observed.

These anti-inflammatory properties of turmeric extract can be credited to their ability to promote the production of complex molecules in the body known as prostaglandins. Prostaglandins regulate or control several processes in the body, including inflammation.[14] Current applications of turmeric as an anti-inflammatory agent include treatment for arthritis, skin conditions, allergies, wounds, tumors, asthma, and rheumatoid arthritis. These chronic inflammatory diseases open opportunities for use in the medical field.[13] One way in which this occurs is the use of turmeric to reduce inflammation post-surgery. This is just one of the several ways that turmeric's properties are currently utilized, opening more possibilities for the future use of turmeric.

Section 3.3: Antibacterial & Antiviral:

Apart from the extensive anti-inflammatory properties of curcuminoids within turmeric, several antibacterial and antiviral properties can be derived by applying turmeric extract to pharmaceuticals.[17] Most scientists are also in high demand for this property of turmeric due to the excessive cost of manufacturing and developing commonly used antiviral medicinal products. The main component of turmeric that is attributed to its antiviral effects is curcumin. Curcumin and its analogs have shown significant ability to provide anti-HIV activity. Curcumin can regulate the HIV-1 integrase, which is the enzyme that allows HIV to replicate. Furthermore, curcumin and the analogs of curcuminoids present in turmeric can be used to prevent the expression of HIV in genes.

Curcumin has also shown the ability to treat and prevent bacterial infections. For example, curcumin has been tested and affirmed to be effective against bacteria, including *B. cereus, B.coagulans, B. subtilis, S. aureus, E. coli*, and *Pseudomonas aeruginosa*, to name a few. A study to determine the effectiveness of curcumin extract from turmeric in preventing microbial and bacterial infections from spreading was done with several strands of bacteria of differing types; the species of bacteria tested were colonies of *P. gingivalis, P. intermedia, T. forsythia, Cytophaga-bacteroidetes*, and *A. actinomycetemcomitans*. These bacteria colonies were placed in agar plates, and each of their respective substances was given to them to promote their growth in the agar media plate. Most of these bacterial strains involve diseases that could arise in the body. Each of these agar media plates was given a dosage of curcumin extract and observed throughout 48 hours. The concentration of curcumin in 10 tubes for a specific strain of bacteria was 100, 50, 25, 12.5, 6.5, 3.12, 1.6, 0.8, 0.4, and 0.2 μL/ml. The tubes of bacteria were also incubated for around 48 hours at 37 degrees Celsius. The qualitative results of this experiment were obtained by visual inspection of each tube after the incubation period to observe the growth at the differing concentrations. These results showed that when curcumin was at dosages of 100 to around 25 μL/ml, depending on the type of bacteria, it showed similar effectiveness in reducing bacterial growth in the tube. Specifically, *A. actinomycetemcomitans* were suppressed by curcumin at dosages of 12.5 ug/ml. However, for *P. gingivalis* and *P. intermedia*, it was only sufficient to prevent growth at the highest concentration of curcumin tested, 100 μL/ml. Lastly, *T. forsythia* demonstrated sensitivity to the effects of curcumin on the bacterial strain at concentrations down to 25 μL/ml. Numerous trials of these tests were also taken to confirm the experiment's results. The significance of this study is that it proved the effectiveness of curcumin's use case in an anti-bacterial medicine in dentistry, pharmaceuticals, or drug development because it can prevent bacterial strains from growing for many types of bacteria at low concentrations depending on the type.

Curcumin found in turmeric extract can provide these benefits through the molecule's interactions with bacterial strains. Specific locations on the curcumin molecule can form hydrogen bonds with the membranes of several bacteria, which may cause damage to it. The cell membranes of bacteria are essential in their function, so curcumin's ability to cause disruptions to this process is a key characteristic that allows it to produce these anti-bacterial results. Additionally, curcumin can disturb the electron transport chain in bacterial cells, another essential component that allows bacterial cells to thrive in the human body.

Section 4: Curcumin in Cosmetics: A Natural and Beneficial Additive:

As corroborated by previous articles, curcumin has exceptionally low bioavailability, which makes it difficult for scientists to study and use curcumin and turmeric for their extensive health benefits. Other than turmeric's health benefits, it has great cultural significance. It is often applied as a paste to the bride and groom after an Indian wedding and to their whole body before the wedding. It is also used as an antibacterial agent and is applied to the severed umbilical cord to prevent bacterial infections in India. Furthermore, in several countries, turmeric is known for its reputation for bringing prosperity and health. Turmeric also is often used in religious settings, such as temples or mosques.

Furthermore, turmeric has immense potential for use in the cosmetological field. Some evidence suggests that turmeric can provide dermatological effects, meaning it can be used as a facial cosmetic if applied/appropriately used. Since turmeric has several pharmaceutical benefits, it also brings these to the cosmetological field, being able to be used as a healthy additive to cosmetic products. Some evidence indicates that turmeric, when added to moisturizers, can lighten skin and prevent lipids on the skin. Also, a gel made using curcumin has shown evidence of promoting apoptosis of cells with DNA damage, which is agreed upon by many sources. Research is being done to determine the efficacy of curcumin as a hair coloring agent, and there is potential. These uses would be impactful to the cosmetic industry due to the positive effect adding curcumin would have on cosmetics in general. Also, turmeric being an environmentally friendly substance adds to the list of benefits turmeric has when added to a cosmetic. Adding onto the possibilities of turmeric as a cosmetic additive, turmeric has shown extensive dermatological benefits. A test was done using curcuminoids found in turmeric to discover the potential of turmeric as an anti-inflammatory addition to cosmetics, and the toleration of the curcuminoids of turmeric within patients was done using proper experimental procedures (randomized, double-blind placebo, controlled trial).[18] The results were that turmeric was well administered and received by the patients, which is crucial information to know if turmeric can be used as a cosmetic. Overall, turmeric has shown efficacy as an antimicrobial, antiparasitic, and antiviral agent. It is important because it allows scientists and researchers to investigate how spice can be used in the cosmetic field as an environmentally friendly and beneficial additive to cosmetic products.

Section 5: Curcumin in the Culinary World:

Curcumin and turmeric are well known for their culinary usage in several cultures, and they are often used in India as a spice and constituent of curry powder. In the US, it is a food additive to various food products. Since meat products often harvest a desirable environment for bacterial and fungal activity, turmeric can be used to prevent this due to its anti-bacterial affinity. This antibacterial capability of turmeric is due to its constituent molecules, primarily curcumin. Several tests on turmeric show that it can remove or treat bacterial infections, and overall anti-bacterial activity has been demonstrated through using turmeric extracts.[19] Curcumin can do this because of its innate effectiveness in forming hydrogen bonds with bacterial cells and parts, allowing curcumin to disrupt the bacteria's processes. A few examples of bacteria that turmeric was shown to be effective against are *Bacillus coagulans, Bacillus subtilis, Bacillus cereus, Staphylococcus aureus, Pseudomonas aeruginosa*, and *Escherichia coli*. This information is extremely useful in the culinary field to ensure that food products are not consumed by bacterial activity within them and to ensure the preservation of food products for an extended period. In addition, research has shown that even at high doses, curcumin and turmeric are still safe and effective, making them an important and valuable addition to foods.

Section 6: Curcumin in Agriculture: A Potential Pesticide:

There is evidence for the possible use of turmeric as a pesticide. This is an interesting and novel property of turmeric that has not been researched thoroughly. Turmeric may have a repellent ability against noxious mosquitoes.[20] There is potential for turmeric to be used as a natural pesticide to protect crops. This would be incredibly useful for agriculture, as it would be cheaper and more environmentally friendly.

Conclusion

Overall, turmeric has shown great efficacy as an antimicrobial, antiparasitic, and antiviral agent. This is important because it allows scientists and researchers to investigate how spices can be used in the cosmetic field as an environmentally friendly and incredibly beneficial additive to cosmetic products. The research presented in this review underscores the vast potential of curcumin as a therapeutic agent. While challenges such as bioavailability remain, ongoing research into novel formulations and delivery systems offers promising solutions. The intricate molecular mechanisms through which curcumin exerts its effects, particularly its interactions with inflammatory pathways, bacterial membranes, and viral replication machinery, provide a solid foundation for future investigations. By addressing the remaining questions and optimizing curcumin's therapeutic potential, we can unlock new avenues for improving human health and well-being through this remarkable natural compound. While extensive, the current research on turmeric and curcumin still leaves many unanswered ques

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tions. Further investigation is needed to fully elucidate the precise mechanisms underlying curcumin's pleiotropic effects and to develop more bioavailable and targeted formulations. These advancements will be crucial in harnessing the full power of curcumin to improve human health and well-being.

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