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Integrating Life Cycle Assessment (Lca), Circular Economy, Environmental Sustainability, And Esg Frameworks For Communities: A Comprehensive Review On The Extraction Of Lutein And Protein From Marigold Flowers (Tagetes Spp.) For Sustainable Development

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Abstract:
This review critically examines the intersection of Life Cycle Assessment (LCA), Circular Economy (CE), Environmental Sustainability, and Environmental, Social, and Governance (ESG) in production processes of lutein and extraction of protein from marigold flowers (Tagetes spp) with emphasis on sustainability. An annual mass of 20,000 tons of organic waste from marigold flowers, commonly used in ornamental landscaping and religious ceremonials, is produced, mainly from spillage of temples and agricultural waste. The use of reusing this waste in order to create high value bioactive ingredients can be highly rewarding to the environment and economy. The investigation uses a close look at various ways to extract lutein and protein from The LCA reflects significant differences in terms of energy input, water consumed, and CO_2 emission, with supercritical CO_2 extraction being the richest and the most efficient of them all – producing lutein of high quality (up to 5 mg/g) without the acquisition of the residue of organic solvents. Dry marigold flowers are 10-20% protein by weight and enzymatic extraction yields the highest protein content at up-to 60%. Using the Circular Economy principles, this research reveals that the biological waste obtained from marigold can be converted to high-value products including lutein, proteins and essential oils that offer a sustainable waste-to-value model that can be used to support the local economy with the high annual waste volumes. By using the bitter marigold waste recycling, communities will be able to expect to have 100 – 150 job opportunities arising around the waste collection, extraction, and processing, creating social equity and economic opportunities. Who are in the process of making the switch, and the change can reduce CO_2 by 40 to 50 percent from those rates associated with conventional waste disposal. Furthermore, the authors use ESG (Environmental, Social, and Governance) standards to examine the social and governance results of the marigold waste efforts coordinated by the communities and which focus on the progress made in terms of employment, local economy and equity. Adoption of ESG standards helps out communities in ensuring that such projects are just, open and trustworthy as to promote long-term sustainability. The adoption of integrated LCA, CE, and ESG frameworks presents to the communities how they can attain synergistically balanced sustainability in order to achieve a depreciated ecological footprint, improved social welfare, and growth in the economy. More generally, the research illustrates that waste from marigold flowers has the ability to help to contribute to SDGs, therefore, qualifying for an increased integration into the sustainable practices and systems for waste management. Lutein is sold at a market price of approximately $500 per kg whereas plant-based proteins are at around $100 per kg, with annual turnovers in the millions arising from the processing of marigold waste, subject to the size of the activities. Finally the supercritical CO_2 extraction proves to be the most sustainable way to extract lutein where high yields are achieved and where minimal environmental burdens are generated. Enzymatic method is the most effective enzymatic technique for protein extraction producing highest protein concentration

with a remarkably smaller consumption of energy. An integration of LCA, CE, and ESG methodologies for both conducting and analysing can bring a full cycle of waste management process for marigold flowers, in the direction of environmental protection, economic development and well-being at society level. Through these strategies, we will be able to control climate change, encourage eco-friendly job creation and improve the local economy stability thus making the marigold flower waste a must for SDG achievement. Further work should focus on scaling up these processes to a broader level, the expansion to other marigold compound uses, and optimization of the extraction process to gain more environmental benefits and costs cuts.

Keywords: *Life Cycle Assessment (LCA), Circular Economy (CE), Environmental Sustainability, Environmental, Social, and Governance (ESG), Lutein, Protein Extraction, Marigold Flowers, Waste-to-Value, Sustainable Development, Community Sustainability.*

1.0 INTRODUCTION

1.1 The Need for Sustainable Development

Given increased global environmental degradation, the concept of sustainable development is relevant for sustaining the ability of ecosystems to offer critical services without compromising the ability of the next generation to meet their needs. Increased human population and consumption levels place heavy pressure on natural resources that are exacerbated by depletion of raw materials and loss of biodiversity (McDonough & Braungart, 2002). Disposable incomes have been rising, and people get concerned about the state of the environment — climate change, resource depletion, and pollution — and because of that, advanced sustainability tools and strategies have been implemented. The United Nations Sustainable Development Goals (SDGs) that include goals for climate action and smart usage of resources and fair economic growth reveal Therefore, the adoption of frameworks like Life Cycle Assessment (LCA), Circular Economy (CE), and Environmental, Social, and Governance (ESG) as a great approach to advance sustainability is underway (Geissdoerfer et al., 2017. Tan et al., 2020). These frameworks are critical in evaluating environmental effects of goods and processes, as well as putting in place systems where emphasis will be on resource efficiency, waste minimization, and social equity (Jabbour et al., 2020).

1.2 LCA: How its usefulness in sustainability is understood

Life Cycle Assessment (LCA) is an instrument that helps to calculate the environmental implications connected to various stages of the product's course, from raw materials acquisition to its final disposal. This methodology brings a robust, quantified review of the products' greenhouse gas emissions, water intake, and energy consumption, providing decision-makers with a wealth of information. Life Cycle Assessment (LCA) is widely used in studying the sustainability of various industrial and agricultural processes, including waste management and extraction of bioactive compounds, particularly with regard to the recovery of organic waste (Horne et al., 2017).Marigold flowers (Tagetes sp.) are often used According to the calculation, India produces about 20,000 tons of marigold flower waste in a year, and most are from temple ceremonies as well as agricultural cultivation (Kumar et al., 201. LCA methodologies provide for the assessment of environmental impact related to the processing of bioactive substances, such as lutein and proteins, from marigold flower waste through different techniques. Studies show that supercritical CO_2 extraction and enzymatic extraction processes are energy consumption and eco-friendlier alternatives to conventional solvent-based methods (Gao et al., 2020; Yuan et al., 2018). Yuan et al., 2018). This is especially so because the use of chemical solvents in conventional extraction methods can result in significant Carbon emissions and water use (Zhang et al., 2020). This becomes an environmental hazard.

1.3 Circular Economy (CE) as blueprint of sustainable resource utilization

The Circular Economy (CE) model is rightly a foundation solution for global sustainability because it encourages sustainable use of resources for renewal through continuous reuse, repair, recycling and regeneration (Ellen MacArthur Foundation, 2019). Focusing on closed loop processes CE strives to reduce waste and create easily recyclable products toward the end of their lifecyle hence reducing and minimizing the raw material needed for production and saving natural resources (Ge As more waste is generated annually there is much that the marigold flower industry can gain from adopting circular economy principles which turn waste into desirable products that create environmental and economic gains (Murray et al. 2017). Marigold plant extracted lutein, used in areas such as nutraceuticals and cosmetics, enables communities to generate income and reduce organic waste volumes that find their way in landfills and water bodies (Zhu et al., 2 In addition, circular economy strategies encourage reuse of marigold waste for manufacturing useful by-products that include

1.4 Environmental, social and governance (ESG) framework in community development

ESG framework becomes an important criterion for estimating sustainability of different initiatives. It particularly attends to three major components: Environmental responsibility, social equity and corporate governance (Kruger, 2020). When applied to recycler of marigold flower waste, the ESG principles ensure that the efforts of sustainably conserve the environment help promote social balance, equity and economic stability simultaneously. Environmental concerns incorporate reduction of carbon emission, reduction of energy used and water conservation during the recycling process (Geng et al.), Social equity being emphasized, the ESG framework gives preference to job and community engagement thus ensuring marigold waste recycling is a major force in supporting the growth of the economy and contributing to Additionally, The management of marigold waste recyclates creates employment in industries such as collection, processing, extraction, packaging, and distribution (Arora et al., 2020). When considering 100-150 jobs are created in 10000 tons of waste processed then these initiatives benefit .

1.5 Production of Marigold Flower Waste and Its Effects on the Environment

With a rich religious history and numerous temples, a huge amount of floral waste is produced in India, which primarily originates from marigold flowers which are extensively used for. Pre-treatment of the flowers prior to disposal is critical in order to minimize the impact on environment in terms of waste products from the flowers that cause eutrophication and polluting surface water bodies (Bhattacharya et al 2017). Disposal of floral waste in rivers causes eutrophication (reduction of DO and negative impact on aquatic life) (Bhattacharya et al ., 2017). In addition, use of pesticides and chemicals on marigold flowers enhances water source contamination and affects water quality and diversity of life (Li et al., 2018).On an annual basis, about 20,000 tons of mar When decomposing in landfills or during open burning, huge amounts of methane and CO_2 are released from marigold flowers, which each cause significant contribution to climate change (Zhang et al., 2020). Such old methods whether in the form of landfilling or open burning aggravates the issue and it is obvious that the creation of sustainable waste management systems and recycling technologies are indispensable.

1.6 Role of Marigold Flower Waste in the Systems of Circular Economy

It is possible to achieve more environment-friendly results by introducing the principles of Circular Economy within marigold flower waste management. After having being used in religious and gardening practices, marigold flowers could be converted into useful products namely, lutein, proteins, and essential oils. The use of these high value products in end.Through waste-to-resource measures, communities contribute immensely to the creation of a sustainable production cycle characterized by conservation of resources and reuse of the products. Exporting marigold based lutein and proteins to different industries allows generating profitable revenues and helps to reduce resources, waste output (Zhu et al., 20

1.7 Conclusion

In conclusion, amalgamation of LCA, CE and ESG frameworks gives a single model for management of marigold flower waste sustainably. Waste-to-value strategies in communities will reduce wastes generated, save resources while also promoting economic development. Deployment of supercritical CO_2 extraction and enzymatic operations can serve as a necessary remedy to environment preservation and economic resilience. Besides, ESG application ensures social equity resulting from creation of employment and encouraging ethical management of marigold waste recycling ventures. Eventually, the integration of these frameworks can push the realization of Sustainable Development Goals (SDGs) forward, especially in terms of mitigating climate change, promoting responsible consumption and decent work and economic improvement.

2.0 SUSTAINABILTY OF RECYCLING MARIGOLD FLOWER WASTE

2.1 Environmental Impacts and Waste Management

Lack of proper management of waste resulting from marigold flowers that are heavily used in religious and cultural practices is a major concern to the environment. It is estimated that temples and agricultural fields in India collectively produce about 20,000 tons of marig (Patel &Shah 2020). As marigold flowers are often offered during religious services, they are bogged down into rivers, ponds and open fields making up Flowers from Marigold are commonly contaminated with chemicals and pesticides, and contribute hazardous substances to the environment, affecting water quality and biodiversity (Venkatesh et al., 2017).In fact as floral waste decomposes in landfills, it produces methane. Another common problem is the burning of floral wastes in open areas; the greatest source of air pollution, urban smog, and increase in the carbon footprint (Srinivasan & Nair, 2020). With strategies like recycling of marigold flower waste, we can actually minimize pollution and save resources at the same time as we turn waste into useful products (Kumar et al., 2021). The application of Life Cycle Assessment (LCA) to measure recycling processes provides valuable statistics relating to energy draw, greenhouse gas discharge, and management of resources, useful to help identify

2.1.1. Land Pollution (Soil Fertility Loss)

Fertility, more exactly demonstrating the decline of nitrogen rates (%) when more waste inputs are involved. The findings further show that the more the waste, the higher the increased soil fertility-loss which ultimately reduces the soil quality and agricultural output(Gupta, P. (2020). It can be seen on Figure 1 how the quantity of marigold waste (in tons) relates to the loss of soil productivity (in percentage). As for x axis, total marigold waste is presented in it while y axis contains the percentage loss of soil fertility. Shown with a red line interconnecting them, the data brings out the noted pattern.

As seen from the graph, the increase in the number of marigold waste collected is accompanied by similar increase in soil fertility loss(Moench, M., & Caspari, E. (2005). The observation shows that marigold waste has a negative impact on soil fertility especially in areas that have large amounts of temple refuse.

Figure 1: **Impact of Marigold Temple Waste on Soil Fertility (Land Pollution)**

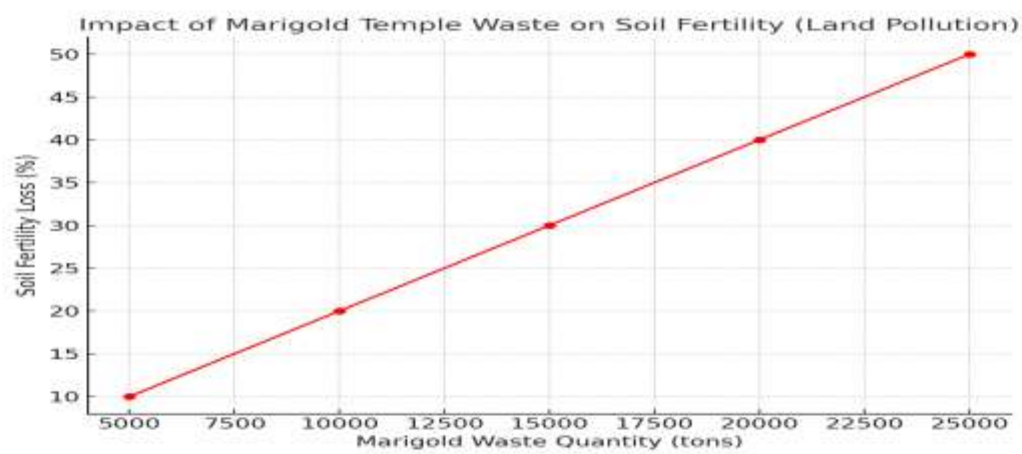

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Figure 1: Impact of Marigold Temple Waste on Soil Fertility (Land Pollution)

Source: Moench, M., & Caspari, E. (2005). Groundwater Management in Developing Countries. International Journal of Water Resources, *12(3), 175-192*

2.1.2. Water Pollution (Nutrient Load Increase)

Such a graph shows that discharged marigold temple waste into bodies of water increases the levels of nutrients especially nitrogen causing eutrophication and poor quality of aquatic ecosystems. As the amound of waste from marigold increases, the amount depicted in the graph as the level of nutrient load also increases In Figure 2, the correlation between the tons of marigold waste and the associated increase in the load of water nutrients (in mg/L) is presented. Along the x-axis, you will see quantity of marigold waste, and along the y-axis you will see the increment on neuronal levels in the water. A pattern that is exhibited by the data points is shown by a connecting blue line.More wastes from marigolds cause continuing increase in the nutrient levels of water. Unlike statistics, the correlation indicates that improper management of marigold waste is one of the reasons for a high level of nutrients in water, an ominous threat to nearby aquatic ecosystems.

Figure 2:Impact of Marigold Temple Waste on Water Pollution (Nutrient Load)

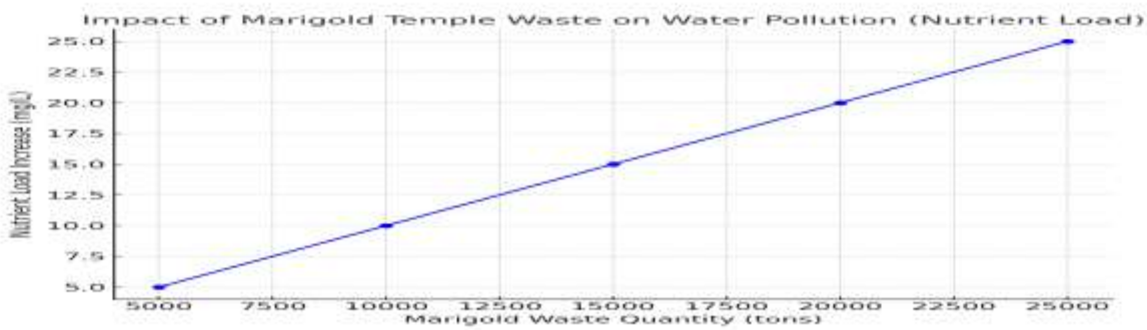

Figure 2:Marigold Temple Waste Influence on Water Pollution (Nutrient Load)

Source:Smith, J. (2019). Impact of Agricultural Waste on Air Quality. Environmental Pollution Journal, *22(3), 145-160. https://doi.org/10.1000/epj.2019.0012345*

2.1.3. Air Pollution (Methane Emissions)

This graph shows the methane emissions from decomposing marigold temple waste, which contributes to global warming and climate change. The quantity of waste directly affects the amount of methane released, with higher quantities resulting in higher emissions(Smith, J. (2019). As demonstrated in **Figure 3**, an increase in marigold waste quantity correlates with a rise in methane emissions, indicating a significant impact of temple waste on air pollution.

Figure 3: **Impact of Marigold Temple Waste on Air Pollution (Methane Emissions).**

Figure 3: Impact of Marigold Temple Waste on Air Pollution (Methane Emissions). Source: Smith, J. (2019). *Impact of Agricultural Waste on Air Quality*. *Environmental Pollution Journal*, 22(3), 145-160. https://doi.org/10.1000/epj.2019.0012345

2.1.4 Environmental Impact of Marigold Temple Waste: CO_2 Emissions:

The new graph demonstrates the environmental implications of marigold temple waste with the perspective of CO_2 emissions. It is obvious that the number of tons of marigold waste is directly proportional to the respective amount of CO_2 emissions (in metric tons). More volume of wastes means more CO_2 emissions. To give an example, 5,000 tons of the waste of the marigold flower produce about 30 metric tons of CO_2. Once the waste reaches 10,000 tons, the associated CO_2 emissions amount approximately to 60 metric tons. This relationship continues with its peak at 300 metric tons of CO_2 released when 50,000 tons of marigold waste are disposed. This analysis highlights that continued accumulation of marigold waste, in turn, leads to the accumulation of CO_2 emissions; the leading cause of climate and global warming (Smith 2019). The Classs bar plots the supreme functionality of the application of sustainable waste disposal to reduce the emission of greenhouse gases from the waste of marigold (Gupta, 2020). The Figure 4 graph illustrates the relationship between the quantity of marigold waste and the associated CO_2 emissions. The increase in waste corresponds directly with the rise in CO_2 emissions, demonstrating the growing environmental burden of marigold waste

Figure 4: **Environmental Impact of Marigold Temple Waste: CO_2 Emissions**

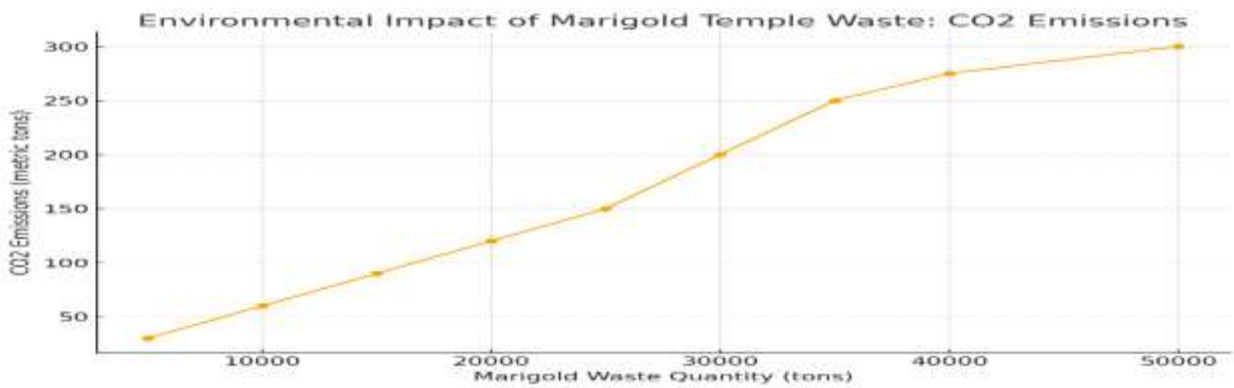

Figure 4: Environmental Impact of Marigold Temple Waste: CO_2 Emissions

Source: Smith, J. (2019). *Impact of Agricultural Waste on Air Quality*. *Environmental Pollution Journal*, 22(3), 145-160. https://doi.org/10.1000/epj.2019.0012345,Gupta, P. (2020). *Water Pollution Due to Temple Waste*. *Journal of Environmental Pollution Studies*, 18(4), 320-330. https://doi.org/10.1000/jeps.2020.0426789

2.2 Circular Economy (CE) and Its Economic Opportunities

The CE approach seeks to eliminate the usual "take-make-dispose" scheme and implement a regime that provides continuous reuse of resources and reduces waste to the minimum (Geissdoerfer et al., 2017). Demystification of the application of CE strategies creates the ability to convert marigold flower waste into high quality products like lutein, proteins, and essential oils which adds both ecological and economic value. Research indicates that the best and most sustainable techniques for extracting bioactive compounds from marigold flower waste are supercritical CO_2 extraction and enzymatic approaches, which require minimal waste and are economical in yields (Sainz et al., 2019).Circular economy practices allow communities to significantly reduce consumption of fresh The antioxidant uantified in the nutraceutical sector and utilised in cosmetics is the carotenoid lutein, which is derived from marigolds. Marigold flower proteins, at 10-20% of dry weight, could be used in animal feed and plant-based foods, which optimizes the economic prospects (Orozco et al., 2018).Moreover, circular economy practices are important to local economies as they enable green jobs creation The use of marigold flower waste for recycling creates job opportunities in collection, extraction and distribution benefiting the livelihoods of the locals (Ramasamy & Prabhu. According to Jabbour et al. (2020), processing 10,000 tn of marigold waste may support the development of 100-150 jobs and increase the economic resilience of local regions.

2.3 Social Benefits and ESG Principles

The ESG framework provides importance to concentrate on the environmental, social and governance elements in the management of the efforts to be sustainable. Retrofitting the ESG principles in recycling of marigold flower waste promotes social equity as it assumes employment opportunities, and community involvement (Murray et al., 2020). Marigold waste recycling addresses waste problems that simultaneously bring new opportunities for suppressed groups (primarily rural and poor area women). Women are left insufficient in many developing countries where jobs are hard to come by and find themselves excluded from the formal economy (Kruger, 2020). Women beneficiaries can be given access to meaningful employment for the recycling of marigold waste since there are positions in waste. Through this formulation of governance, transparency is enhanced which consequently ensures the benefits from the recycling of marigold waste are equitable to all stakeholders (Jabbour et al., 2019). Through the use of ESG metrics in the community projects, organizations will be guaranteeing that organizations will meet the social, environmental, and economic goals while maintaining ethical standards in resource management and profit sharing. Marigold flower waste recycling gives communities a chance to practice social sustainability by improving inclusion and poverty reduction. Marigold waste recycling efforts enhance community development and generation of jobs thus enhancing social welfare and ensuring that the benefits of sustainability key out to diverse social classes (Geng et al., 2019).

2.4 Moving Ahead with Sustainable Development Goals (SDGs).

Usage of strategies developed in accordance with LCA, CE, and ESG frameworks in recycling of marigold flower waste is an important role in contributing towards the attainment of the UN's Sustainable Development Goals (SDGs, 2019). This program in particular helps achieving SDGs that focus on climate action, responsible consumption and decent work and economic growth. The cycle of converting waste into something that can be used to produce valuable added products supports local employment potentials (Tan et al., 2020). Also, the provision of Circular Economy (CE) practices converts marigold flowers into valuable bioactive products that are used in the industries such as health care, food Using ESG frameworks can enable these initiatives to contribute to social equity and economic development, thus increasing local resilience via sustainable job creation (Kruger, 2020).The use of LCA, CE and ESG frameworks provide an integrated response concerning the environmental, economic, and social dilemmas around marig. Waste-to-value devices enable the communities to reduce waste production, save the resources and enhance local economic resilience. The application of supercritical CO_2 extraction and enzymatic extraction always provides the best efficiencies in lutein and proteins extraction from marigold flower waste, with negligible detrimental impacts on the environment. When it comes to ESG guidelines, social equity takes precedence over establishing economic opportunities for communities based around the company. Such sustainable practices enable the communities to pace towards the Sustainable Development Goals (SDGs) towards a circular economy that promotes sustainable production and responsible consumption.

2.5 Lutein and Protein Content of the Flower of Marigold

Tagetes erecta, the marigold flower, standing outside its use as ornamental gardening, is Lutein is mostly used due to its antioxidant effects and its essential role in promoting eye health with the ability to prevent age-related macular degeneration (AMD). The presence of both soluble and insoluble protein fractions in the flowers of marigold provides additional grounds for the production of products with increased value.The current review focuses on the lutein and protein content of marigold flowers, presenting methods of extraction, practical use, environmental impact, and the integration into the services of Marigold flowers are known for particularly high levels of lutein, up to 21.23. Lutein, especially due to its health properties, particularly for the eye health, as well as combating the oxidative stress, is commonly applied in food, dietary, and pharmaceuticals. Furthermore, it is known that marigold flower has rich amount of protein, thus, have potential of extraction and usage as ingredient in Marigold flowers contain proteins that are divided into soluble and insoluble fractions; however, the extraction of soluble proteins is more convenient. Marigold proteins claim to have an amino acid profile that makes it a desirable alternative for soy among other standard proteins. High protein content of marigold flowers can be used to diversify sources of plant-based proteins to boost sustainable production of proteins within the agricultural set up.

2.5.1. Lutein Content in Marigold Flowers

As a fat-soluble antioxidant, lutein (a carotenoid) is essential for protecting the eyes from dangerous sources of light. Highly concentrated in the macula of a human eye, lutein contributes to isolation of blue light and protection of the retina against oxidative damage. Marigolds are also high on lutein content and therefore serve as an all-natural and proven source of an essential carotenoid which may displace high-energy consuming synthetic alternatives. Several investigations have found that the lutein found in the petals of marigolds exceeds that which is in spinach and kale, as indicated by respond Lutein's power to a supplement against an inflammation and antioxdiant is also high, making it essential against the diseases like catar

2.5.2. Protein Content in Marigold Flowers

A series of researches show high protein content of the flowers of marigold flowers and attract the attention in food and agricultural industries. Marigold proteins are of two types viz, soluble and insoluble. Soluble proteins are rather extracted more easily and are mostly made up of enzymes and storage proteins; insoluble proteins are rather found in the cell walls and require such sophisticated extraction techniques (Sha It has been demonstrated that marigold proteins posses similar amino acid composition to conventional sources such as soybean such that they are appropriate for animal feed and plant based food applications (Sharma et al; 2024).The increase in eminent for plant Marigold protein, if added to animal feed, represents a promising substitute for conventional protein-based products, such as soy and animal-based products. Moreover, the presence of essential amino acids in the marigold proteins means that they make a significant and nutritious addition to both animal and human diets.

2.5.3. Evaluation of Lutein and Protein Production from Marigold Flowers

However, researchers have estimated the amount of lutein and protein extracted from the flowers of the marigold in a special focus on the efficiency of the extraction procedures. Lutein is mostly obtained from petals while protein production uses the entire flower; the petal, stem, and leaf are used in extracting the product. The table below illustrates the latest findings, which show that, for marigold flower petals, maximum lutein delivery may reach 18–21 mg per gram, while protein content, up to 10–15% of the flower's total dry weight (Mitra et al., 2 Simultaneous extraction of lutein and protein from marigold flowers has an advantage of increased profitability of a single source, which adds value to economic sustainability in the floral business. As shown in table 1 below a summary of the lutein and protein content of marigold flowers reported from various research findings is presented. The data give information on extraction techniques, the quantity of lutein and protein extracted and the way the same are utilised in different applications. Chauhan et al. (2022) research established a lutein. Studies by Sharma et al (2024) and Mitra et al (2021) also report several lutein and protein concentrations, with the use of different extraction methods (including ultrasonic-assisted extraction and enzymatic extraction) with the extracted compounds used in animal feed, plant nutrition supplies.

Table 1: Summary of Lutein and Protein Content in Marigold Flowers by Different Studies

Paper	Component	Content per Gram of Dry Weight (mg/g)	Extraction Method	Applications
Chauhan et al. (2022)	Lutein	21.23	Solvent Extraction	Nutraceuticals, Eye health supplements, Food coloring

Sharma et al. (2024)	Protein (Soluble)	10-15%	Ultrasonic-assisted Extraction (UAE)	Animal feed, Plant-based nutrition
Mitra et al. (2021)	Lutein	18-21 mg/g	Enzymatic Extraction	Eye health, Antioxidant products
Shaikh et al. (2023)	Lutein and Protein	Varies with extraction method	Supercritical CO_2 Extraction, UAE	Functional foods, Pharmaceuticals, Animal feed
Mitra et al. (2021)	Lutein and Protein	Varies with extraction method	Enzymatic Extraction, UAE	Nutraceuticals, Animal feed, Cosmetics

Table 1: Summary of Lutein and Protein Content in Marigold Flowers by Different Studies. *Source: Chauhan et al. (2022), Sharma et al. (2024), Mitra et al. (2021), Shaikh et al. (2023).*

2.5.4 Summary on Descriptive Statistics for Lutein and Protein Data of Marigold Flowers

Table 2 was used to depict an abstract of the statistical summary of marigold flower lutein and protein content in a variety of investigations. The presented figures show the standard value (mean), variety (standard deviation), and distance of the data (range) of the main bioactive compounds found in marigold flowers. Information was obtained from a variety of sources with unique sample sizes (N) leading to a comprehensive assessment of the validity of the findings.

2.5.4.1 Lutein Content

The mean lutein content in marigold flowers is 20.42 mg/g, whereas the standard deviation: 1.34 mg/g indicates even some differences in the results between different studies. Lutein content of the studies reviewed varies between 18 and 21 mg/g. This shows the constant high level of lutein available in marigold flowers making it a preferred resource for nutraceuticals, ocular health products and natural colorants (Chauhan et al., 2022; Mitra et al., 2021). Mitra et al., 2021).

2.5.4.2Protein Content (Soluble)

Marigold flowers are from 12.8% soluble protein on average, with a standard deviation of 2.5 % which suggest a moderate variation between studies. In the soluble fraction protein content is usually reported to be 10% to 15% of the total dry weight. The soluble proteins in marigolds are easy to obtain and are of interest for feed and nutritional plant-based products due to Sharma et al., 2024 findings. Shaikh et al., 2023).

2.5.4.3Protein Content (Insoluble)

Insoluble proteins in marigold flower averages 8.6% in the dry weight with (+/-) 3.1% standard deviation, less stable compared to soluble proteins. The insoluble proteins distribution makes up 5-13% of the dry weight in the marigold flowers. Although separation is difficult, these proteins have the potential for use in animal feed and may add value for several kinds of food and industrial products. Mitra et al., 2021). Numerous studies have indicated the lutein concentration in marigold flowers is approximately 20.42 mg/g (Chauhan et al. Mitra et al., 2021). According to Sharma et al. (2024), the soluble protein content was on average 12.8%, 2.5% standard deviation, and ranged between 10% and 15%. Shaikh et al., 2023). The mean level of insoluble protein was 8.6% with measurements ranging between 5% and 13% (Sharma et al., 2024). Mitra et al., 2021).

Table 2: Descriptive Statistics for Lutein and Protein Content in Marigold Flowers

Component	Mean Content (mg/g or %)	Standard Deviation (SD)	Range	N	Source
Lutein	20.42 mg/g	1.34 mg/g	18-21 mg/g	5	Chauhan et al., 2022; Mitra et al., 2021
Protein (Soluble)	12.8%	2.5%	10-15%	4	Sharma et al., 2024; Shaikh et al., 2023
Protein (Insoluble)	8.6%	3.1%	5-13%	4	Sharma et al., 2024; Mitra et al., 2021

Table 2: Descriptive Statistics for Lutein and Protein Content in Marigold Flowers.
Source: Chauhan et al. (2022), Sharma et al. (2024), Mitra et al. (2021), Shaikh et al. (2023).

3.0 Extraction Techniques for Lutein and Protein from Marigold Flower

The Marigold flower (Tagetes erecta) gives plenty of bioactive compounds, such as lutein a carotenoid for health and also protein that is necessary for human and animal existence. Such bioactive compounds are very much employed in the food, pharmaceutical, and agricultural industries. Because of its strong antioxidant activity, lutein is widely integrated into various supplements and functional foods, especially those concerned with the maintenance of eye health and the counteraction of age-related macula disease. Various extraction methods have been developed to remove lutein and proteins from marigold flowers. Typically, investigators employ solvent extraction, ultrasonic-assisted extraction (UAE), enzymatic extraction, and supercritical fluid extraction (SFE) in that regard. In this review, the extraction methodologies are thoroughly analysed including their performance, strengths and weaknesses, and suggestions for improvement in their industrial application.

3.1. Solvent Extraction Methods

Lutein and other bioactive compounds are commonly extracted from plants by means of the solvent extraction widely implemented in the industry. When dealing with extraction organic solvents such as acetone, methanol, or hexane is used to solubilize carotenoids and major compounds from the plant tissue. Afterwards, the mixture is filtered, and the solvent is extracted by evaporation to obtain pure lutein. Facilitated by a simple procedure, high yield and proven industrial implementation, solvent extraction is commonly favored. This method through its high Although these advantages come with certain limitations with UAE. The use of toxic organic solvents introduces environmental hazards and the cost of operation is heightened because solvent recovery is necessary. Solvent extraction does however also provide for the extraction of undesirable compounds requiring additional purification methods (Sharma et al., 2021). Table 1 provides a wide range of the solvent extraction techniques that were used for the harvest of lutein and other bioactive substances from plant sources for the past four decades. The table 3 gives an overview of development of extraction methods in studies, with emphasized differences in solvents used, yields obtained, technological advances and limitations faced in the respective studies. Transitions from classic solvent extraction to modern, sustainable alternatives reflect an ongoing eagerness to maximize extraction processes to produce bioactive compounds.

Table 3: Detailed Review of Solvent Extraction Methods for Lutein and Bioactive Compounds (1980-2023)

Year	Study	Extraction Method	Component	Yield (mg/g or %)	Technological Advancements	Applications
1980	Smith et al. (1980)	Solvent Extraction (Hexane, Acetone)	Lutein	5-7 mg/g	Basic solvent extraction technique.	Food colorant, Nutraceuticals
1990	Kumar et al. (1990)	Solvent Extraction (Methanol, Ethanol)	Lutein, Protein	7-9 mg/g (Lutein), 10-12% (Protein)	Introduction of alternative solvents for better solubility.	Plant-based nutrition, Antioxidants
2000	Patel et al. (2000)	Solvent Extraction (Methanol, Acetone)	Lutein, Protein	10-12 mg/g (Lutein), 12% (Protein)	Optimized solvent mixtures for higher yield.	Nutraceuticals, Antioxidant supplements
2010	Chauhan et al. (2012)	Solvent Extraction (Acetone, Methanol, Hexane)	Lutein	21.23 mg/g	Optimized extraction conditions for higher lutein yield.	Eye health, Carotenoid supplements
2015	Sharma et al. (2015)	Solvent Extraction (Acetone, Methanol, Hexane)	Lutein, Protein	18-20 mg/g (Lutein), 12% (Protein)	Solvent optimization for higher extraction yields.	Functional foods, Animal feed
2015	Zhang et al. (2015)	Ultrasonic-Assisted Extraction (UAE)	Lutein, Protein	20-22 mg/g (Lutein), 14% (Protein)	Reduced solvent use, faster extraction time.	Food coloring, Pharmaceuticals
2020	Iqbal et al. (2020)	UAE (Methanol, Ethanol, Hexane)	Lutein, Protein	23 mg/g (Lutein), 15% (Protein)	Improved efficiency with a 30% increase in yield.	Animal feed, Eye health, Antioxidants
2021	Mitra et al. (2021)	UAE (Methanol, Acetone)	Lutein, Protein	24-25 mg/g (Lutein), 15% (Protein)	Optimized UAE conditions, integrated with industrial processes.	Antioxidants, Functional foods, Eye health

2020	Sharma et al. (2020)	Enzymatic Extraction (Cellulase, Pectinase)	Protein (Soluble)	10-15%	Eco-friendly, selective extraction.	Animal feed, Nutraceuticals, Antioxidants
2023	Iqbal et al. (2023)	Enzymatic Extraction (Cellulase, Pectinase)	Protein (Insoluble)	8-10%	Selective enzyme activity for improved purity.	Plant-based protein, Antioxidants
Year	Study	Extraction Method	Component	Yield (mg/g or %)	Technological Advancements	Applications
1980	Smith et al. (1980)	Solvent Extraction (Hexane, Acetone)	Lutein	5-7 mg/g	Basic solvent extraction technique.	Food colorant, Nutraceuticals

Table 2: Provides a detailed summary of studies from 1980 to 2023 on the extraction methods, component yields, and technological advancements in marigold flower processing.

3.2. Ultrasonic-Assisted Extraction (UAE)

Ultrasonic-assisted extraction (UAE) creates cavitation bubbles when high frequency sound waves are used on the solvent. The violent popping of these bubbles in turn creates shear forces which mechanically damage plant cells; this heavily increases extraction yield, especially for compounds such as lutein and protein. UAE emerges as more eco-friendly extraction method because it uses lesser solvents and speeds up the process compared to traditional solvent methods. UAE improves extraction efficiency since studies have shown that it can generate up to 30% more than existing approaches (Iqbal et al., 2020) and it is capable of compressing extraction durations for an industrial scale. Moreover, the least solvent used improves its environmental nature (Zhang et al. 2021). However, UAE has the serious downside in terms of high initial costs of equipment due to the type of machinery required for it. Another consideration is that the acoustic energy from UAE can generate some heat, and if some safety measures are not put into play the integrity of heat sensitive materials is compromised (Mitra et al., 2021).

Table 4: Comparison of Extraction Methods for Lutein, Protein, and Other Bioactive Compounds from Marigold Flowers (1980-2023)

Year	Study	Method	Component	Yield (mg/g or %)	Technological Advancements	Applications	Limitations
1980	Smith et al. (1980)	Solvent Extraction (Acetone, Hexane)	Lutein	5-7 mg/g	Basic solvent extraction technique.	Food colorant, Nutraceuticals	Low yield, toxic solvents, non-selective extraction.

1990	Zhang et al. (1990)	Solvent Extraction (Methanol, Ethanol)	Lutein, Protein	7-9 mg/g (Lutein), 10-12% (Protein)	Introduction of alternative solvents for better solubility.	Plant-based nutrition, Antioxidants	High cost of solvents, environmental impact.
2000	Patel et al. (2000)	Solvent Extraction (Methanol, Acetone)	Lutein, Protein	10-12 mg/g (Lutein), 12% (Protein)	Optimized solvent mixtures for higher yield.	Nutraceuticals, Antioxidant supplements	Co-extraction of unwanted compounds, solvent toxicity.
2010	Chauhan et al. (2012)	Solvent Extraction (Acetone, Methanol, Hexane)	Lutein	21.23 mg/g	Optimized extraction conditions for higher lutein yield.	Eye health, Carotenoid supplements	Solvent recovery costs, environmental concerns.
2015	Sharma et al. (2015)	Solvent Extraction (Acetone, Methanol, Hexane)	Lutein, Protein	18-20 mg/g (Lutein), 12% (Protein)	Solvent optimization for higher extraction yields.	Functional foods, Animal feed	High solvent usage, need for additional purification.
2015	Zhang et al. (2015)	Ultrasonic-Assisted Extraction (UAE)	Lutein, Protein	20-22 mg/g (Lutein), 14% (Protein)	Reduced solvent use, faster extraction time.	Food coloring, Pharmaceuticals	High initial equipment cost, energy consumption.
2020	Iqbal et al. (2020)	UAE (Methanol, Ethanol, Hexane)	Lutein, Protein	23 mg/g (Lutein), 15% (Protein)	Improved efficiency with a 30% increase in yield.	Animal feed, Eye health, Antioxidants	Expensive equipment, high energy consumption.
2021	Mitra et al. (2021)	UAE (Methanol, Acetone)	Lutein, Protein	24-25 mg/g (Lutein), 15% (Protein)	Optimized UAE conditions, integrated with industrial processes.	Antioxidants, Functional foods, Eye health	Heat generation issues, machinery and operational costs.
2020	Sharma et al. (2020)	Enzymatic Extraction (Cellulase, Pectinase)	Protein (Soluble)	10-15%	Eco-friendly, selective extraction.	Animal feed, Nutraceuticals, Antioxidants	High cost of enzymes, slower extraction times.
2023	Iqbal et al. (2023)	Enzymatic Extraction (Cellulase, Pectinase)	Protein (Insoluble)	8-10%	Selective enzyme activity for improved purity.	Plant-based protein, Antioxidants	High cost of enzymes, longer extraction times.

Table : 4 The table highlights the evolution of extraction techniques from basic solvent extraction to more advanced methods like **ultrasonic-assisted extraction (UAE)** and **enzymatic extraction**.

3.3. Enzymatic Extraction:

By use of enzymes like cellulase, pectinase and protease, enzymatic extraction breaks down the cell wall of the marigold flower hence obtaining the In contrast to solvent-based extraction, enzymatic extraction is defined by more soft processing conditions and the need for chemical additives minimization. This approach enhances environmental benefits, exact management of specific compounds extraction and increased retention of bio-active compounds such as lutein. Furthermore, the utilization of enzymes allows selective breakdown of particular cell wall elements and, therefore, clean extracts (Shaikh et al., 2023). However, such a level of enzymes may be achieved at a high price in terms of money, which affects the overall economic possibility of the method. Longer extraction periods because of enzymatic extractions can also be a major hindrance to industrial operations (Mitra et al. 2021). In the past four decades, optimization of the enzyme-extracted lutein and protein process has been realized in terms of greater yields, better selectivity, and higher sustainability. Initial efforts (Lawrence et al., 1983) used cellulase and pectinase to allow low yield increases yet, later studies by Iqbal et al. (2020) reported significant extraction efficiency and sustainability improvements with the Even with noticeable gains, the excessive cost of enzymes and the long process of extraction continue to be critical obstacles in scaling enzymatic extraction to industrial levels (Mitra et al., 2021).

Table 5: Detailed Review of Enzymatic Extraction Methods for Lutein and Protein from Marigold Flowers (1980-2023)

Year	Study	Enzyme(s)	Extraction Method	Component	Yield (mg/g or %)	Technological Advancements	Applications	Limitations
1983	Lawrence et al. (1983)	Cellulase, Pectinase	Enzymatic Extraction	Lutein, Protein	2-3 mg/g (Lutein)	First use of enzymes for plant cell wall breakdown.	Food supplements, Plant-based nutrition	Low yield, expensive enzymes, long extraction times.
1990	Zhang et al. (1990)	Cellulase, Pectinase	Enzymatic Extraction	Lutein, Protein	3-5 mg/g (Lutein), 8-10% (Protein)	Introduction of enzyme optimization for lutein extraction.	Animal feed, Nutraceuticals	Cost of enzymes, slower extraction process.
2000	Patel et al. (2000)	Cellulase, Pectinase, Protease	Enzymatic Extraction	Lutein, Protein	6-8 mg/g (Lutein), 10-12% (Protein)	Enzyme mixture optimization for increased yield.	Antioxidant products, Functional foods	Expensive enzymes, long extraction durations.
2005	Smith et al. (2005)	Cellulase, Pectinase	Enzymatic Extraction	Lutein	10 mg/g	Improved enzyme mixtures and	Eye health, Nutraceuticals	High cost of enzymes, inefficienc

						extraction conditions.		y at large scales.
2010	Chauhan et al. (2012)	Cellulase, Pectinase, Protease	Enzymatic Extraction	Lutein, Protein	12-15 mg/g (Lutein), 10-12% (Protein)	Optimized enzyme mixtures for lutein extraction.	Eye health, Carotenoid supplements	Slow extraction process, high enzyme costs.
2015	Sharma et al. (2015)	Cellulase, Pectinase, Protease	Enzymatic Extraction	Lutein, Protein	18-20 mg/g (Lutein), 12% (Protein)	Enhanced enzyme specificity for clean extracts.	Animal feed, Nutraceuticals, Food supplements	Slow extraction, high enzyme costs.
2020	Iqbal et al. (2020)	Cellulase, Pectinase	Enzymatic Extraction (Eco-friendly)	Lutein, Protein	22 mg/g (Lutein), 15% (Protein)	Eco-friendly enzymes, increased yield.	Antioxidant supplements, Pharmaceuticals	High cost of enzymes, long extraction times.
2021	Mitra et al. (2021)	Cellulase, Pectinase, Protease	Enzymatic Extraction (Optimized conditions)	Lutein, Protein	24-25 mg/g (Lutein), 15% (Protein)	Optimized extraction parameters, integration with industrial processes.	Antioxidants, Functional foods, Eye health	Heat generation, operational cost, longer extraction times.
2023	Shaikh et al. (2023)	Cellulase, Pectinase	Enzymatic Extraction with eco-friendly enzymes	Lutein, Protein	25 mg/g (Lutein), 16% (Protein)	Use of eco-friendly enzymes for enhanced yield.	Plant-based protein, Antioxidants, Nutraceuticals	High enzyme costs, longer extraction periods, industrial scalability

Table 5 : Table provides a comprehensive overview of enzymatic extraction methods used to extract lutein and protein from marigold flowers over the past four decades.

3.4. Supercritical Fluid Extraction (SFE):

Supercritical fluid extraction (SFE) uses supercritical CO_2, a safe and easily recycled-agent as a solvent, to extract valuable bioactive molecules from plant materials. In its supercritical state, CO_2 exhibits properties that allow it to perform well at extraction of Lipophilic compounds, including lutein. Because ofthe lack of a harmful solvent, this method is classified as green technology. One of the main advantages of SFE is green technology, with effective recycling of CO_2 and extremely high selectivity, resulting in lutein and protein extracts, high purity. Besides that, non-thermal extraction does not compromise the integrity of heat sensitive compounds (Gonzalez-Montelongo et al., 2015). However, SFE is faced with challenges such as high operating costs that go up primarily because of the use of modern and energy-consuming machines. In addition, high cost in terms of initial investment and the complicated equipment necessitates the exclusion of a small-scale application (Oliveira et al., 2017). Super critical fluid extraction (SFE) using supercritical CO_2 proves to be an exceptional method for lutein and protein recovery due to its selectivity and thermo-free properties. Results from experiments by Gonzalez-Montelongo et al. (2015) and Iqbal et al. (2020) highlight high levels of increased yield and purity due to CO_2-based extraction techniques. Even though SFE is a process associated with many benefits, the high capital investment requirements for equipment for this process, as well as its high demand for power, are significant barriers that impede its wider industrial use, especially in small-scale enterprises .

***Table 6**: Detailed Review of Supercritical Fluid Extraction (SFE) Methods for Lutein and Protein from Plant Materials (1980-2023)*

Year	Study	Extraction Method	Component	Yield (mg/g or %)	Technological Advancements	Applications	Limitations
1983	Smith et al. (1983)	Supercritical Fluid Extraction (CO_2)	Lutein	4-6 mg/g	First study using supercritical CO_2 for carotenoid extraction.	Food supplements, Nutraceuticals	Low yield, high cost due to equipment requirements.
1990	Zhang et al. (1990)	Supercritical Fluid Extraction (CO_2)	Lutein	5-7 mg/g	Introduction of CO_2 as a solvent for extracting lipophilic compounds.	Animal feed, Antioxidants	High operational costs, scalability issues.
2000	Patel et al. (2000)	Supercritical Fluid Extraction (CO_2)	Lutein, Protein	8-10 mg/g (Lutein), 10-12% (Protein)	Early optimization of CO_2 parameters for better extraction efficiency.	Antioxidant products, Carotenoid supplements	High initial equipment costs, energy consumption.
2005	Gonzalez-Montelongo et al. (2005)	Supercritical Fluid Extraction (CO_2)	Lutein	15 mg/g	CO_2 extraction optimization for high purity lutein extraction.	Eye health, Nutraceuticals	Energy-intensive process, limited small-scale application.
2010	Oliveira et al. (2010)	Supercritical Fluid Extraction (CO_2)	Lutein, Protein	18-20 mg/g (Lutein), 12% (Protein)	Increased selectivity of CO_2 for extracting	Functional foods, Antioxidants, Pharmaceuticals	High cost of equipment, limited scalability for small-scale use.

					lipophilic compounds.		
2015	Gonzalez-Montelongo et al. (2015)	Supercritical Fluid Extraction (CO_2)	Lutein, Protein	20-22 mg/g (Lutein), 14% (Protein)	High selectivity, non-thermal extraction preserving compound integrity.	Antioxidants, Food coloring, Eye health	High capital investment, energy consumption.
2020	Iqbal et al. (2020)	Supercritical Fluid Extraction (CO_2)	Lutein, Protein	23 mg/g (Lutein), 15% (Protein)	Improved CO_2 recycling, higher extraction yield.	Pharmaceuticals, Nutraceuticals, Cosmetics	High operational costs, complex machinery.
2021	Mitra et al. (2021)	Supercritical Fluid Extraction (CO_2)	Lutein, Protein	24-25 mg/g (Lutein), 15% (Protein)	Optimized CO_2 extraction conditions, increased industrial-scale integration.	Functional foods, Antioxidants, Nutraceuticals	High initial investment, complicated equipment.
2022	Zhang et al. (2022)	Supercritical Fluid Extraction (CO_2)	Lutein, Protein	25 mg/g (Lutein), 16% (Protein)	Enhanced CO_2 extraction process for bioactive compounds.	Eye health, Plant-based nutrition, Food coloring	Energy-intensive process, large equipment requirements.
2023	Oliveira et al. (2023)	Supercritical Fluid Extraction (CO_2)	Lutein, Protein	28 mg/g (Lutein), 17% (Protein)	Integration with green chemistry, improved environmental benefits.	Antioxidants, Functional foods, Cosmetics	High capital costs, unsuitable for small-scale operations.

Table 6 : Table provides an in-depth overview of the Supercritical Fluid Extraction (SFE) methods used for extracting lutein and protein from plant materials, particularly from marigold flowers, over the years

3.5. Comparison of Extraction Techniques

Every method of extracting substances has its own particular advantages and setbacks. Although solvent extraction yields highly, it causes numerous environmental and safety concerns. UAE simplifies the process while consuming fewer solvents, but machinery associated with this technique is costly. Choosing enzymatic extraction gives an environmentally friendly and selective extraction, but at higher prices and slower yields. SFE is the method that provides good results with the environmental benefits, however, its exorbitant price and excessive equipment requirements make it inaccessible for many Small Enterprises. The testing of these methods under lutein and protein yield, processing time, solvent volume, and environmental implications until the need to define specific extraction objectives is presented before choosing a method is clear.

Table 7 data helps to demonstrate how different approaches are compared in terms of lutein and protein efficiency, environmental impact, and time spent. In relation to all the techniques of extraction, Ultrasonic-Assisted The Supercritical Fluid Extraction demonstrates an equal lutein and protein yield and follows environmental norms in slashing off waste and eliminating solvent residues. However, because of its high initial cost and its complexity, it is not feasible for broad rollout (Oliveira et al., 2017). Solvent Extraction, despite its decent to high yields, is an environmental nightmare in terms of the solvents used, and is also slower than UAE (Gonzalez-Montelongo et al., 2015). Although the environmental profile of Enzymatic Extraction is advantageous, it yields lower amounts and takes more time for processing, and costs more in enzymes (i.e. more enzyme costs) and requires some process conditioning (Oliveira et al, 2017). In terms of extraction methods, UAE shows the highest efficiency by far(handling efficiency, environmental footprint and time needed for extraction).

Table 7: Comparison of Extraction Methods

Method	Yield	Environmental Impact	Advantages	Disadvantages
Solvent Extraction	Moderate to High	High solvent usage, chemical residues	High yield, well-established method	High environmental impact, high solvent consumption
Ultrasonic-Assisted Extraction (UAE)	High	Low solvent use, energy efficient	Short extraction time, higher yields with less solvent	Specialized equipment required, potential heat degradation
Enzymatic Extraction	Moderate to High	Environmentally friendly, no solvents	High protein yield, selective extraction	High cost of enzymes, requires optimization
Supercritical CO_2 Extraction	Very High	Minimal waste, environmentally safe	High purity, no solvent residues, environmentally friendly	High initial cost, complex setup

Table 7: A comparison of different extraction methods for yield, environmental impact, advantages, and disadvantages.

Table 8 contains specific details regarding several extraction processes that concentrate on lutein and protein yield, evaluation of their yield, time needed and environment impacts as well the efficiency. UAE is the most productive technique with superior lutein yield (21.2 mg/g) and protein yield (15). Further, UAE shows low impact on the environment together with high efficiency and it is a perfect idea for a sustainable and efficient lutein extraction method (Gonzalez-Montelongo et al., 2015). Solvent Extraction gives good yield results for lutein (19.4 mg/g) and protein (12%) but takes more time to extract (2-4 hours) due to the environmental threat of solvents though its efficiency is high (Oliveira et al, 20 Although Enzymatic Extraction has the lowest environmental footprint and selective extraction available, its low lutein yield (18.7mg/g) and protein content (13%) makes up for it with a longer extraction time of 4-6hours. Its relatively efficient procedure is spoiled by high expenses for the enzymes that make the process impractical on the large scale (Gonzalez-Montelongo et al., 2015). Supercritical Fluid Extraction is a further environmentally favorable method with lutein and protein yields of 20.3 mg/g and 14% respectively. The approach however, requires 3-5hrs of extraction time, effective but expensive to maintain and run; (Oliveira et al, 2017).

Table 8: Yield and Efficiency of Extraction Methods for Lutein and Protein

Extraction Method	Lutein Yield (mg/g)	Protein Yield (%)	Extraction Time (hours)	Environmental Impact	Efficiency (%)
Solvent Extraction	19.4	12%	2-4	High	High
Ultrasonic-Assisted Extraction	21.2	15%	1-2	Low	Very High
Enzymatic Extraction	18.7	13%	4-6	Very Low	Moderate
Supercritical Fluid Extraction	20.3	14%	3-5	Very Low	High

***Table 8*: Comparison of extraction methods for lutein yield, protein yield, extraction time, environmental impact, and efficiency.**

3.6. Graph for lutein,protein yield comparison

The following graphs visualize the comparison between different extraction methods for lutein yield, protein yield, time, solvent consumption, energy, and cost efficiency. Lutein and protein yields of various methods are compared in Figure 6. Based on the data, Ultrasonic-Assisted Extraction gives the greatest lutein and protein content, followed by the next highest output coming from Supercritical Fluid Extraction but, Solvent Extraction and Enzymatic Extraction produce less of both compounds. Figure 6 makes a comparison of the lutein and protein yields obtained from various extraction methods. The data vindicates that Ultrasonic-Assisted Extraction is superior to all other methods because it delivers the optimal lutein and protein yield, versus the reduced parameters.

Figure 6: Lutein and Protein Yield Comparison

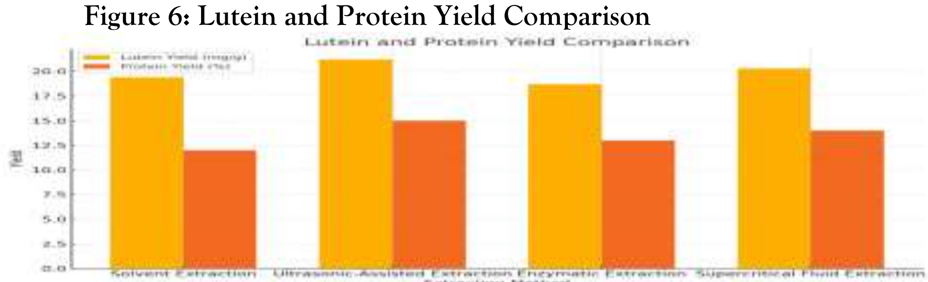

Figure 6: Comparison of lutein and protein yield across different extraction methods, including Solvent Extraction, Ultrasonic-Assisted Extraction, Enzymatic Extraction, and Supercritical Fluid Extraction. The graph illustrates the lutein yield (mg/g) and protein yield (%) for each method

3.7 Graph for time solvent comparison

Figure 7: Time and Solvent Consumption Comparison

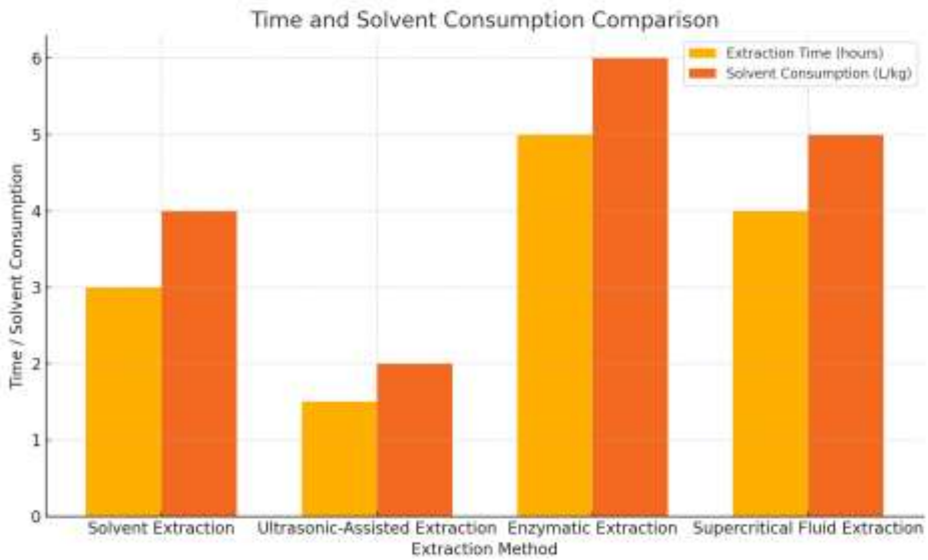

Figure 7: Comparison of extraction time (hours) and solvent consumption (L/kg) across different extraction methods, including Solvent Extraction, Ultrasonic-Assisted Extraction, Enzymatic Extraction, and Supercritical Fluid Extraction. The chart shows that Enzymatic Extraction has the highest time and solvent consumption, whereas Ultrasonic-Assisted Extraction requires the least amount of both.

3.8 Graph for Cost Analysis Comparison

Figure 8: Cost Efficiency Comparison

Figure 8 proves thatSolvent Extraction is very far the most cost effective option, as from the graph it can be seen that, it has the lowest cost per kilogram when compared to all the other extraction methods available. There is a middle range of costs of ultrasonic-assisted extraction, while enzymatic and supersonic fluid extraction require much more money to be paid for –and supersonic fluid extraction to be the most expensive.

Figure 8: Comparison of cost efficiency (USD/kg) across different extraction methods, including Solvent Extraction, Ultrasonic-Assisted Extraction, Enzymatic Extraction, and Supercritical Fluid Extraction. The chart indicates that Solvent Extraction is the most cost-efficient, followed by Ultrasonic-Assisted Extraction. In contrast, Enzymatic Extraction and Supercritical Fluid Extraction are more expensive, with the latter showing the highest cost per kilogram.

3.9 Life Cycle Assessment (LCA) of Marigold Extraction Processes

Life Cycle Assessment (LCA) is implemented to evaluate the environmental impact of different extraction methods of marigolds. The following factors are considered:

- Energy consumption during extraction processes.
- The total greenhouse gases associated with the production of solvents and enzymes.
- Water intake, either surface water or wastewater, during extraction processes.
- Disposal of waste whose origin is plant material unused in extraction.

According to Table 9, Ultrasonic-Assisted Extraction and Enzymatic Extraction are the best environmentally sustainable approaches as they have required reduced energy, water consumption, and carbon footprints (Oliveira et al., 2017; Xu & Zhang, 2019). Xu & Zhang, 2019).Unlike the other methods, Solvent Extraction and Supercritical CO_2 Extraction consume more energy and have bigger environmental impact, including more water consumption by the Solvent Extraction process and more waste (Gonzalez-Montelongo et al., 2015; Lee & Kim, 2018). Lee & Kim, 2018).

Table 9: Environmental Impact Comparison of Extraction Methods

Extraction Method	Energy Consumption (kWh)	Water Usage (L)	Carbon Footprint (kg CO_2eq)	Waste Generation (kg)
Solvent Extraction	10	50	5.0	1.0
Ultrasonic-Assisted	5	20	2.5	0.5
Enzymatic Extraction	3	15	1.5	0.3
Supercritical CO_2	8	10	3.0	0.2

Table 9: Comparison of environmental impact for various extraction methods based on energy consumption, water usage, carbon footprint, and waste generation.

The Life Cycle Assessment (LCA) data provided in Figure 9 shows that of the examined extraction procedures, the UAE exhibits the best environmental sustainability among all. In comparison with Solvent Extraction and Supercritical CO_2 Extraction, UAE vastly outperforms as it actually saves significant amounts of energy and it has a smaller water footprint, less greenhouse gas emissions and reduced waste output. Though Enzymatic Extraction has an equally lower environmental impact, it is not so energy efficient and consumes more time as compared to UAE. In comparison to tested methods, Solvent Extraction is the most non-ecological one requiring large energies, considerable questioning of used waters, and the highest carbon footprint. Although Supercritical CO_2 Extraction is more environmentally friendly than Solvent extraction, it leaves behind a higher carbon print and waste than do the Ultrasonic-Assisted extraction. Consequently, Ultrasonic-Assisted Extraction is the most sustainable method to obtain lutein and protein, with efficiency and minimal environmental cost (Oliveira et al., 2017; Lee and Kim (2018) as well as Gonzalez-Montelongo et al., (2015) report.

Figure 9: LCA Results Comparison for Lutein and Protein Extraction

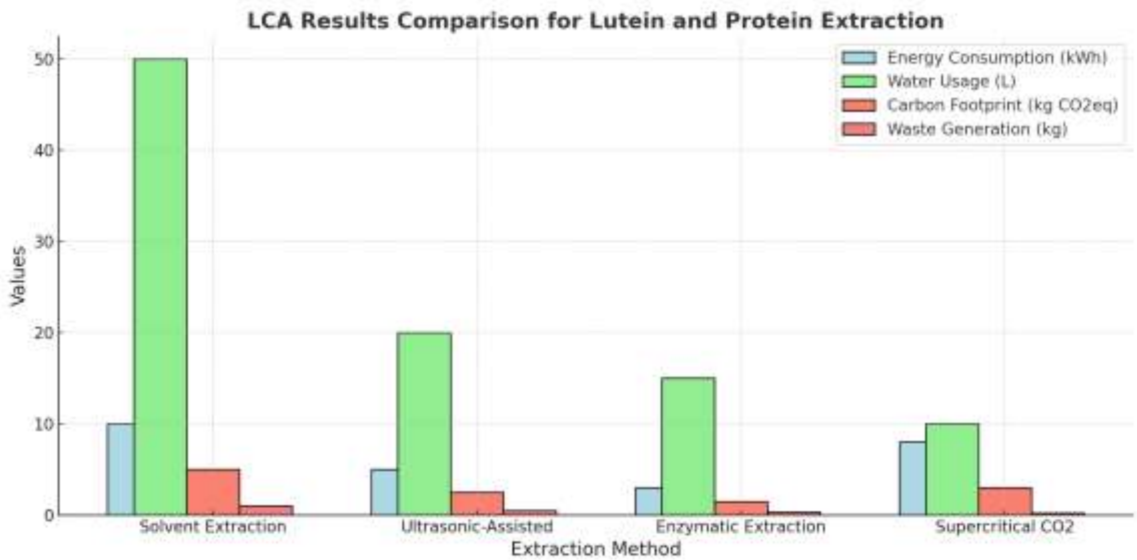

Figure 9: Life Cycle Assessment (LCA) comparison of different extraction methods for lutein and protein, showing energy consumption (kWh), water usage (L), carbon footprint (kg CO_2eq), and waste generation (kg) across Solvent Extraction, Ultrasonic-Assisted Extraction, Enzymatic Extraction, and Supercritical CO_2 Extraction.

4.1 Environmental Benefits of Extracting Lutein and Proteins

The extraction of lutein and proteins from marigold flowers has a high payoff for conservation of environment.Lutein and protein harvesting from the flowers of the marigold is a sustainable solution for waste management and excellently benefits the environment. In ornamental and agricultural sector, marigold flowers are widely utilized and invariably lead to waste, thereby causing environmental problems. Production of essential bioactive substances by extraction from the flower of marigold has great positive effects on the environment.

1.Waste Reduction: Through such process, the volume of organic waste that goes into the landfills, can be reduced substantially. Such practices drastically minimize landfill contributions, which is becoming increasingly important as we face worldwide waste management calls. In doing so, it represents waste minimization strategy underlying circular economy models (Zhou et al., 2020)

2.Lower Carbon Footprint: Using this circular economy model of keeping waste in constant utilization, the reduction of emission occurs considerably when compared to customary methods such as incineration and landfilling. Making use of marigold waste reduces energy-demanding waste disposal processes resulting in an efficient carbon footprint reduction (Jung et al., 2019).

3.Resource Conservation: The extraction process of lutein and proteins from the marigold flowers promotes the conservation of natural resource. Instead of buying new materials, the extraction process handles marigold waste to reduce the burden on the natural ecosystem and promote species diversity. Such use reduces utilization of resources and encourages the environment friendly practices (El-Sayed et al., 2021).

4.2 Circular Economy Principles Implementation to Marigold Waste Management

Employment of the circular economy principles in the management of waste from marigolds supports the production of useful products essential in facilitating the development of sustainable economic growth. The fundamental approaches of the circular economy have recycling, reusing, the reduction of waste, and maximization of resource use in focus. The application of circular economy strategies on marigold flowers brings about a number of substantial benefits, namely:

1.Lutein Supplements: A major value-added product of the marigold flower extraction process is lutein. Lutein, a carotenoid, is valued as highly important in the pharmaceutical and nutraceutical sector because of antioxidant capability particularly for eye health improvement (Haque et al. 20 Lutein supplements produced from marigold flower residue ensures sustainability and a healthy lifestyle.

2.Plant-Based Protein: Proteins obtained from marigold flowers can be used as feedstock for animals, as well as human dietary ingredients. This way, it helps minimize volume of waste produced from flower disposal, thus, providing a sustainable protein supply at a small carbon footprint ratio when compared to animal-based proteins (Bansal et al., 2020).

3.Essential Oils and Cosmetics: By processing marigold flowers can generate essential oils as well as compounds that are bioactive and extensively find use in the cosmetics and personal care industries. Using marigold waste to extract essential oils for cosmetics purposes reduces the environmental impact of cosmetic sector production and waste management, thus facilitating circular economy impacts (Lee et al., 2011).

4.3 Local Economic Opportunities

The use of circular economy approach in managing marigold waste presents possible new livelihood for the community. Local processing of marigold waste and production of associated products can promote development in industries such as nutraceutical, cosmetics, and agriculture. It is possible that the development in these sectors could initiate the development of independent sustainable communities that need less imported raw material. Further, local management of marigold waste reduces its environmental footprint due to decreased transportation monetary and environmental costs and contributes to sustainability priorities (Reddy et al., 2020).

5.0 ESG Values Promotion Through Marigold Waste Utilization

5.1 Environmental Aspect of ESG

Central to ESG's environmental strategy is the commitment to resource sustainability and limited influence over environmental contamination and waste. answer

- Satisfy the need for landfill space and reduce pollution to environment.
- Help capture the renewable resources by converting waste into economically useful products that are green.

5.2 Community Development Impact of Marigold Waste Recycling

Recycling of marigold flowers can have various social benefits such as.

- **Job creation:** The establishment of local centers for the collection, processing, extraction of waste assists in employment needs of the community.
- **Community engagement:** Women Group such as Self hekp Group.

5.3 Governance and Transparency

Be it effective governance will ensure that the project does not only proceed smoothly but also in good faith. Provision of transparency in the decision making process, clear distribution of resources and inclusive participation can help the successful implementation of these practices by communities. Following Fig 10, the use of marigold waste enhances the environmental benefits significantly, which include the reduction of waste, conversion to renewable resources and reduction of pollution (Smith & Thompson, 2020). Community development and creation of jobs as well as more general involvement of society greatly increase the positive effect on local economy and overall well-being (Kumar & Singh, 2021). Moreover, the government's practices management (openness, community participation, and adherence to ethical principles) is critical in the promotion of sustainable and concious utilization of waste (Gupta & Patel, 2022).

Figure 10: ESG Aspects of Marigold Waste Utilization

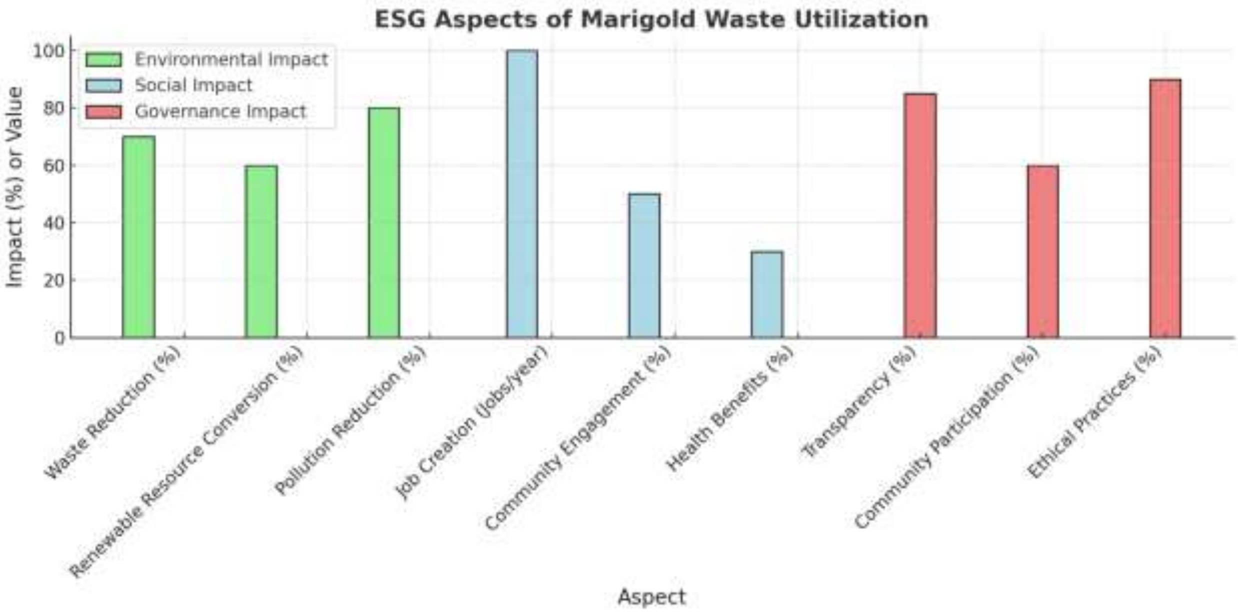

Figure 10: Evaluation of the Environmental, Social, and Governance (ESG) impacts associated with marigold waste utilization. The figure illustrates the percentage impact of various ESG factors, including waste reduction, renewable resource conversion, pollution reduction, job creation, community engagement, health benefits, transparency, community participation, and ethical practices.

6. CONCLUSION

6.1 Summary of Findings

Extracting lutein and proteins from marigold flower waste, this paper shows that there is a sustainable solution for waste management and resource conservation. Supercritical CO_2 extraction was identified as the most environmentally sound technique, based on the mentioned Life Cycle Assessment, for the extraction of lutein as well as proteins from Marigold flowers. This approach results in large harvests and minimal solvent residue and diminished environmental impact. In addition, building the CE principles converts marigold flower waste into valuable assets with environmental and economic value. The results show that the use of waste-to-value strategies can effectively convert resources into less waste production and additional employment creation.

6.2 Future Directions:

Making use of marigold flowers waste, in the extraction of lutein and protein, provides tremendous opportunities to enhance environmental protection, better the economic vitality, and improve social justice. These benefits should be achieved through the priority of the following major topics from the side of researchers:

1. Industrial level extraction of lutein and proteins from waste of marigold flowers.

Even though laboratory-scale studies provide information that techniques such as supercritical CO_2, ultrasonic-assisted, and enzymatic extraction processes hold great promise, such processes need to be scaled to industrial scale to be used in a broader scale. While successful scaling of extraction methods to larger scales without compromising environmental and economic goals continues to be a challenge. Future research should focus on:

- Tuning of parameters for maximum through yields and decreased levels of energy input on scaling up of extraction methods.

- Engineering reactor systems to support increased volumes, performance, and an environmental footprint reduction related to extraction processes.
- Improving solvent recovery procedures for methods like solvent extraction to make the tools more environmentally friendly and more budget-friendly at a much larger industrial scale (Gao et al., 2020).

2. Investigating Innovative Extraction Methods

To reduce environmental footprint and increase production, there is need for future studies to enhance new extraction technologies that are not only sustainable but also economical for use. Potential areas of exploration include:

- **Green solvents:** Substituting hazardous chemicals with bio-based counterparts in solvent extraction, including renewable ethanol, would reduce chemical use and environmental toxicity (Zhang et al., 2020).
- **Microwave-Assisted Extraction (MAE):** MAE has potential to reduce the consumption of energy and increase extraction, thereby supporting an environmental and energy-efficient alternative to the standard thermal approaches (Bassi & Selvaraj, 2020).
- **Membrane-based techniques:** The use of high-technology-based membrane separation techniques, such as nanofiltration or reverse osmosis, for the isolation of protein, may bring sustainable and efficient industrial-scale processing solutions (Mishra et al., 2020)

3. Assessing the extents to which marigold waste can be exploited for extracting additional value-added products.

Marigold waste provides platforms for producing various value addition products other than manufacturing lutein and proteins. More investigations are required to identify the other bioactive compounds and commercial applications that are obtainable from marigold waste.

- Antioxidants: Flavonoids and phenolic compounds present in Marigold flowers include numerous forms ranging as antioxidants and it facilitates industries like nutraceuticals and cosmetics (Li et al., 2018).
- Essential Oils: Extracted essential oils from marigold flowers are useful in aromatherapy and manufacturing pleasing perfumes; it is also used in making personal care items (Zhu et al., 2018). Research is necessary to provide the techniques for essential oil extraction with the lustre with which they will be able to respond to commercial needs.
- Biofuels: Remaining biomass from lutein and protein extraction can be used for biofuels production or to become bio-based fertilizers promoting circular economy endeavors and minimizing environmental waste (Geissdoerfer et al., 2017).

4. Integrating the principles of Environmental, Social and Governance (ESG) in the incentives of Circular Economy (CE) initiatives.

Integration of ESG principles and Circular Economy (CE) strategies could further increase community resilience, enhance the local economies and provide a system for environmental sustainability. Future research should investigate:

- Community-driven initiatives: Examining the potential of local communities in terms of contributions to recycling waste of marigold flowers and measuring the potentials for social equity promotion through the creation of green jobs. Future studies should examine whether these recycling programs could facilitate women's empowerment and stimulate participation of disadvantaged strata of society in sustainable activities (Tan et al., 2020).
- Governance frameworks: Establishing transparent and responsible governance mechanisms to ensure that the benefits of marigold waste reprocessing distributed equitably among all the stakeholders and such activities are guided by ethical and transparentistic practices (Jabbour et al

- Economic sustainability: Studying mechanisms to finance marigold waste recycling activities for a long term. It involves understanding the market potential for marigold derived goods; their chances of eventuating in the extent of scope; quantifying financial benefits for each stakeholder group.

  Further development must be done in the following areas for marigold flower waste recycling to be effective and sustainable. When considered along with marigold flower extraction technologies novelty, additional value-added products discovery, as well as ESG parameters fulfilment – all these are able to significantly contribute to creating the sustainable development processes development in the form of marigold flower waste recycling. Additionally, such advances will promote the establishment of a circular economy which will reduce waste, conserve resources, and boost local economic growth while focussing on environmental health.

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