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Microwave assisted extraction of food colorants: principle, mechanism, extraction technique and applications

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Abstract
In response to the current trend of consumer awareness towards foods containing natural colours, the food industry has moved from synthetic colours to natural colours. In addition, because nontraditional extraction techniques are more environmentally friendly and stable than traditional methods, they are becoming more and more popular for removing pigments from natural sources. The benefits of using microwave-assisted extraction (MAE), a technological advancement that can be heated rapidly and has been demonstrated to be successful in recovering bioactive compounds from a variety of sources, are covered in this review. The primary goals are to: (1) Describe the fundamental ideas and techniques of MAE and endeavor to demonstrate the efficacy and efficiency of this technology in color recovery. (2) A number of elements or variables influencing how well MAE extracts natural pigments from different sources. (3) The use of MAE to extract natural pigments from a wide range of materials, including different fruits, microalgae, flower waste, etc., has significantly increased thanks to the development of integrated technology and novel extraction solvents. The Earth Response Sustainable Development Goals (SDGs) also include research on waste materials and novel pigments (like algae and other organisms) in combination with MAE as a major area of study.

Keywords: Synthetic colorants, Microwave-Assisted Extraction (MAE), waste valorization, novel pigment sources

Introduction

Importance of Natural Food Colorants Food color is a key factor influencing consumer choices and preferences. Colorants, which can be dyes, pigments, or chemicals, are used to impart color to food, medications, cosmetics, or the body, either alone or in combination. They also enhance food safety, quality, and sensory attributes. There are two main types: synthetic colorants (e.g., tartrazine, sunset yellow) and natural colorants from plants, such as chlorophylls, carotenoids, betalains, and flavonoids. Natural pigments can be either lipid-soluble (e.g., carotenoids) or water-soluble (e.g., anthocyanins, betalains).

Plant-derived pigments are increasingly favored over synthetic ones due to their therapeutic properties and lower risk of toxicity. Unlike synthetic colors, which can cause health issues like asthma, eczema, headaches, and hyperactivity, natural pigments offer a safer alternative with fewer allergens and enhanced nutritional benefits. Synthetic pigments, some of which are deemed harmful by authorities like the European Food Safety Authority, carry risks of adverse effects and require warning labels. The growing consumer preference for healthy eating makes research into natural food colorants essential, despite challenges such as instability and poor absorption associated with natural pigments.

Extraction Methods for Natural pigments Microwave-assisted extraction (MAE) is a popular non-conventional method for solid-liquid extraction due to its ease, controlled heating, and rapid extraction times (15-20 minutes). It requires less solvent and offers higher yields, precision, and accuracy, especially for trace compounds like pesticide residues and heavy metals. MAE combined with enzyme-assisted aqueous two-phase extraction (MEAATPE) has shown a 71.14% higher extraction yield compared to other methods like Soxhlet extraction. For extracting lutein from marigold flowers, optimal conditions include 28% ethanol, 20% ammonium sulfate, 0.45 U/g enzyme concentration, 45 °C, 150 minutes enzymolysis time, 120 seconds microwave time, and 270 watts microwave power, yielding 84.61 mg/g total phenolics and 7.32 mg/g lutein with high recovery rates.

Classification of Plant Pigments

Pyrrole derivatives: Chlorophyll Chlorophylls are green photosynthetic pigments found in plants, algae, and cyanobacteria, crucial for fruit ripening and leaf senescence. There are five main classes of chlorophyll (a, b, c, d, and f), with magnesium (Mg) as the central metal in their structure. Chlorophylls have a porphyrin macrocycle with four pyrrole rings and a hydrophobic phytol side chain, while one edge of the porphyrin ring is hydrophilic, enhancing their capacity through conjugated double bonds.

Isoprenoid derivatives: Carotenoids Carotenoids are fat-soluble pigments producing yellow, red, and orange colors, found in plants, fungi, bacteria, and microalgae. They are classified into two main types: β-carotene (with oxygen functional groups, found in lutein and zeaxanthin) and α-carotene (found in xanthophylls, lycopene, and others). Carotenoids are isoprenoid lipids whose color results from conjugated carbon-carbon double bonds in their structure. Geometric isomerization increases Z-isomers, while oxidation degrades carotenoids.

Flavonoid derivatives: anthocyanin Flavonoids, polyphenolic compounds with a 2-phenylchroman core, are well-known for their pharmacological, biochemical, and medicinal properties. Anthocyanins, a type of water-soluble flavonoid, provide red, purple, and blue hues to plants and are crucial for their defense and reproduction. These pigments, derived from the flavyl cation ($C_{15}H_{11}O$), can be glycosylated or polymethoxy derivatives. Key anthocyanidins include cyanidin, malvidin, and delphinidin. Their conjugated bonds are essential for the development of red, blue, and purple colors in plants.

Heterocyclic derivatives of nitrogen

Betalains are nitrogen-based plant pigments derived from tyrosine, comprising two main types: yellow-orange betaxanthins and reddish-violet betacyanins. Betanin, a common betacyanin, is found in beets, while violasexanthin and indicaxanthin are present in cactus pears and yellow roots. Betaxanthins and betacyanins produce colors ranging from orange to red, with absorption maxima at 480 nm and 536 nm, respectively. Betacyanins can undergo acylglycosylation and hydroxyl glycosylation, whereas betaxanthins do not show glycosylation.

Major Food Pigments in flower Plant waste/Parts

Chrysanthemum morifolium Ramat flowers contain bioactive compounds like flavonoids, carotenoids, and caffeoylquinic acids, which exhibit antioxidant, anti-inflammatory, antibacterial, and antifungal properties. The plant, native to China, features a variety of pigments across its colored flowers, including flavones, carotenoids, and anthocyanins. Clitoria ternatea, known as the blue pea, has high levels of anthocyanins and is used for its vibrant blue color in food and packaging. Marigold petals are rich in lutein and polyphenols, with lutein esters making up 70–79% of the total. The cockspur coral flower contains anthocyanins and various phenolic compounds with potential health benefits. Roselle (Hibiscus sabdariffa L.) is a tropical plant known for its carotenoids and anthocyanins, used extensively in food products for its color and antioxidants.

Table 1: Major Pigments present in flower Plant waste/Parts

Pigment	Part of flower Plant	Name of the plant	Amount Present	References
Carotenoids, Flavones& Carotenoids	Petals	Chrysanthemum Morifolium Ramat	32.82 mg/100 g of Flavones	[12]
Anthocyanins	Petals	Clitoriaternatea/Blue Pea or butterfly pea flower	132.756 mg/L of Anthocyanin (Petals)	[15]
Lutein (Carotenoids)	Petals	Marigold (Tagetes Spp.)	20.71 mg /g Lutein present on Dry Basis (d.b.)	[22]
Anthocyanins	Petals	Cockspur Coral Flower	0.843 mg/100 gm of Anthocyanin in Petals	[26]
Carotenoids, Anthocyanins	Calyces	Roselle (*Hibiscus sabdariffa* L.)	2.5g/100 g of Carotenoids & Anthocyanin (Dry weight)	[32]
Anthocyanins	Tepals	Saffron (*Crocus sativus* L.)	136.96±5.7 mg cyanidin-3-glucoside/g tepal	[39]
Betalain, Flavonoids	Floral Bracts	Bougainvillea Glabra	6.02 mg/100 gm of Betalain & Flavonoids in floral bracts of the plant	[40]

Need for Optimum Utilization of Flower waste

India, the leading producer of cut and loose flowers, faced significant waste challenges due to inadequate cold storage facilities, resulting in 40% loss of flower production. In 2014–15, India produced 477 lakh cut flowers and 1641 tons of loose flowers, with daily fresh flower production reaching 4738 tonnes. Key cities like Varanasi and Surat contribute significantly to this waste. Floral waste, rich in organic matter, can be transformed into valuable products through methods such as solid-state fermentation, which produces organic acids, enzymes, biopesticides, and biofuels. Additionally, traditional uses of flowers include making jellies, syrups, and fermented drinks.

Flower waste is valuable for producing various products due to its high sugar content, pleasant aroma, and color. It can be used to create dyes, compost, biofuels, incense sticks, and essential oils. Studies show camellia, rose, and roselle flowers contain significant amounts of soluble sugars (40.5%, 24.3%, and 11.5%, respectively) and carbohydrates (66.0%, 58.7%, and 40.3%). Glucose is the major sugar in these flowers, with camellia at 24.7%, rose at 30.8%, and rosella at 20.0%. Despite its high sugar content (46–48 g/100 g dry weight), mahula flowers are underutilized (Kumar *et al*. 2009).

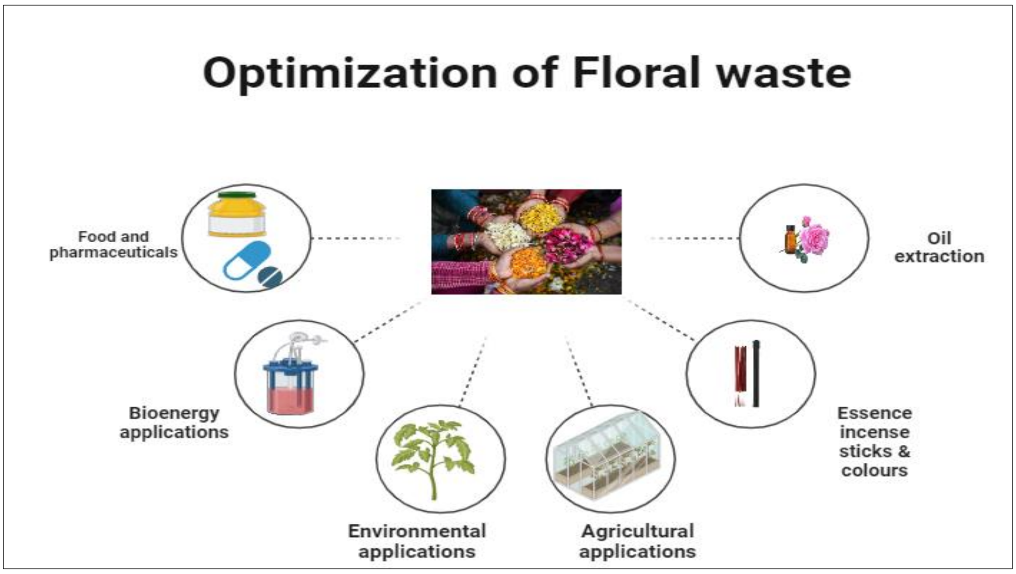

Fig 1: Optimum utilization of floral waste for different applications

Principle & Mechanism of Microwave Assisted Extraction (MAE)

Microwave-assisted extraction (MAE) uses electromagnetic waves, specifically at frequencies of 915 MHz and 2.45 GHz, to heat plant materials through dipole rotation and ionic conduction. This heating is achieved either in a closed container with regulated conditions or an open container where the boiling point of the solvent dictates the temperature. The process involves microwaves causing dielectric heating, which increases thermal energy and enhances extraction efficiency. In MAE, the solvent transfers heat to the solid matrix, leading to the evaporation of moisture, elevated vapor pressure, and ruptured cell walls that release pigments. This method offers a significant boost in extraction rates and efficiency compared to traditional techniques. Additionally, MAE can be adapted to solvent-free systems like in-situ microwave-generated hydro distillation, although using water may introduce challenges like microbial growth and hydrolysis of plant metabolites.

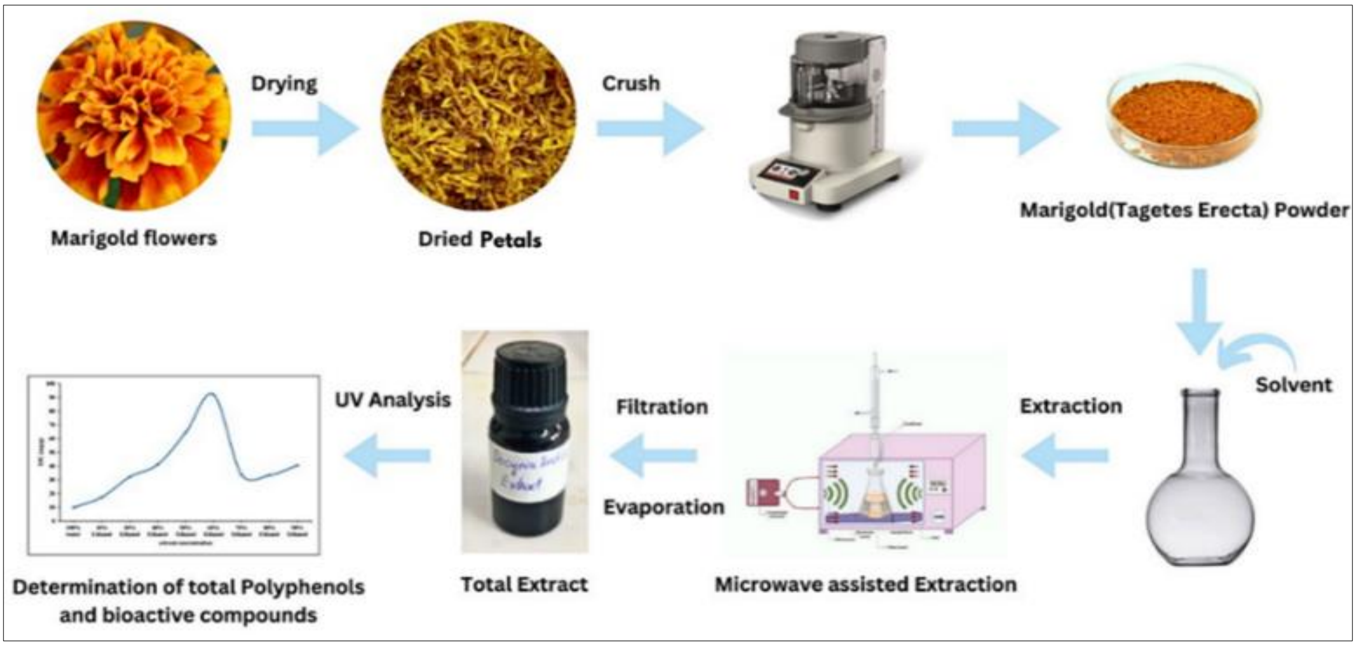

Fig 3: Extraction of Lutein from marigold flowers by using MAE

Factors Affecting Microwave Assisted Extraction of Pigments

Microwave-assisted extraction (MAE) works by using electromagnetic waves to alter biomass structure, increasing efficiency compared to conventional methods. MAE heats the solid matrix directly, creating vapor pressure that ruptures cell walls and releases pigments. In a study, MAE extracted more total monomeric anthocyanins (17.36±0.54 mg/g) and total phenolics (208.28±1.43 mg gallic acid/g) in just 10 minutes with 180 W power, significantly improving yields and reducing extraction time from 24 hours to 15 minutes.

Effect of Solvent Nature

Ethanol, a commonly used solvent, efficiently extracts various secondary metabolites and absorbs microwaves well. For enhanced selectivity, solvent combinations like water, ethanol, and methanol are used. Microwave-assisted extraction (MAE) has been applied to extract anthocyanins from saffron (Crocus sativus). Natural deep eutectic solvents (NADESs), which include compounds like polyalcohol, sugars, and amino acids, offer benefits such as biodegradability, low toxicity, and sustainability. NADESs are increasingly considered for their eco-friendly properties and effectiveness in extracting bioactive compounds, including curcuminoids from C. longa.

Effect of Solid to Liquid Ratio

Natural deep eutectic solvents (NADESs) were tested for extracting curcuminoids, with a 1:1 citric acid to glucose ratio and 15% water at 50 °C, 0.1/10 g/mL solid/liquid ratio, and 30 minutes yielding the highest results compared to conventional solvents. For annatto seed pigments, microwave-assisted extraction was compared to hot aqueous extraction. Optimal conditions for bixin and norbixin extraction were found to be a 1:1 seed-to-water ratio, 30 minutes at 60 °C with microwave assistance, producing 0.625% bixin and 3.008% norbixin. Increasing solvent-to-material ratios beyond optimal levels can lead to uneven distribution and reduced efficiency.

Microwave Power& Temperature

Microwave power and temperature in microwave-assisted extraction (MAE) are closely linked, as the extraction matrix heats up when absorbing microwave energy. This increases the solvent's ability to solubilize solute compounds, enhancing solvent penetration and matrix wetting, which leads to higher pigment yields. However, while increasing microwave power generally boosts extraction yield, it can reach a point where further increases yield diminishing returns or even reduced efficiency due to thermal degradation of compounds. For instance, in extracting anthocyanins from Cockspur Coral flowers, the optimal conditions were a 1:15 feedstock-to-solvent ratio, 600 W power, and 3 minutes of extraction, yielding the highest anthocyanin content. Meanwhile, the highest total phenolic content (132.73 g/L) was achieved with 12 minutes of extraction at the same power level.

Characteristics of the Plant Matrix

The type of plant material used significantly affects extraction efficiency for compounds like nicotine, phenols, and volatile oils. Factors such as plant species, age, and storage conditions influence pigment concentration and accessibility. Understanding plant cellular structure is crucial for effective extraction, as secondary metabolites accumulate in specific tissues or organelles. For instance, traditional phenolic extraction from onions is less effective compared to solvent-free microwave hydro diffusion and gravity (MHG) techniques, which enhance extraction by disrupting cell walls and vacuoles. Key plant characteristics influencing extraction include:

Types of plant cell Plant cells, tissue, and areas of the plant matrix containing bioactive components such as oil glands, bark, etc. are commonly found to have thick walls. Whether a plant is secretory or not, microwave technique can easily destroy it because it releases the bioactive contents of the cell when it is exposed to microwave flux [80].

Plant cell components

Plant leaves and shoots are where plant components like phenols are stored. In order to extract phenol from the plant matrix, the cellular components such as guard cells, epidermal cells, and central vacuoles are separated [81].

Covalent attachment of bioactive components Complex attachment of polyphenol-like bioactive components to plant cell walls is observed through glycosidic linkage [82].

Amount of water The amount of water or moisture retained inside the matrix can significantly improve microwave absorption and promote heating by changing the polarity of the solvent. The physical structure of the matrix may alter as a result of moisture.

Particle Size and Shape

The plant material's particle size should be minuscule, between 100 μm and 2 mm, in order to maximize the sample's contact surface with the solvent [83]. The plant material will then be more surface area for the solvent to penetrate, break the cell, and enhance mass transfer if it is smaller in size [84]. This will result in an extraction that is more effective [85]. assert that the plant material's form is important. After suspended in the solvent, its irregular shape becomes round and smooth. Because the secondary metabolites must diffuse through the stagnant layer the used solvent creates around the plant material, transport may be slowed down.

Effect of Stirring

Agitation is a positive addition to the MAE, improving it even further. This is because there is a direct impact on mass transfer. The extraction efficiency can be increased by continuously agitating the concentrated active compounds, which lowers the mass transfer barrier. By encouraging the release and dissolution of the target compounds, stirring aids in accelerating the extraction rate [86]. Because it involves continuously agitating or stirring the solvent-sample mixture while using a microwave, this step in the extraction process is very important. Agitation can be achieved in several ways, such as using an ultrasonic bath, a mechanical stirrer, or a magnetic stirrer, depending on the size of the extraction.The used solvent then forms a stagnant layer around the plant material, which could slow down transport because the secondary metabolites need to diffuse through it.

Limitations of Micro-wave Assisted Extraction

MAE has several drawbacks that need consideration. Post-extraction, additional separation steps like centrifugation or filtration are often required. The high temperatures involved can damage thermolabile compounds and alter chemical structures, potentially reducing yield. MAE is less effective with non-polar target compounds or solvents and may co-extract unwanted compounds, necessitating further purification. Additionally, the process requires careful optimization of parameters such as temperature, time, and microwave power, which can vary depending on the sample. The setup costs for microwave extraction systems can be high, posing financial challenges, particularly for smaller labs. Moreover, the energy-intensive nature of MAE raises environmental concerns.

Comparison of Extraction Efficiency with Conventional methods of extraction

MAE significantly outperformed conventional solvent extraction (CE) for anthocyanin yield from black currant marc. Optimized MAE conditions (pH 2, 700W, 10 minutes) produced maximum yield in just 10 minutes, compared to 300 minutes for CE, using half the solvent. MAE also increased the final anthocyanin concentration by 20%. Similarly, studies on blue pea flowers confirmed that MAE was the most effective method, yielding 9.61 mg TAC cyanidin-3-glucoside equivalent at 50 °C for 30 minutes.

Microwave assisted extraction of colouring pigments

Microwave assisted extraction of anthocyanin

Microwave-assisted extraction (MAE) has consistently proven to be the most effective method for extracting anthocyanins, yielding significantly higher Total Anthocyanin Content (TAC) and total phenolic content compared to traditional hot-water extraction. Various studies have demonstrated optimal MAE conditions, including 9.61 mg TAC cyanidin-3-glucoside equivalent at a 1:15 ratio, 50°C for 30 minutes; 2.18±0.06 mg/g TAC from blackberries at 469W, 52% solvent, 25 g/mL ratio for 4 minutes; 397.1 mg/100 g TAC from purple maize cobs using 1.5 M HCl, 95% ethanol at 400W for 2 minutes; 5021.47 mg/L anthocyanins from Black Soybean Seed Coat (BSSC) at 569.46W, 40:1 solvent ratio, 262.54 seconds; and 273.284 mg/L TAC from Lavandula pedunculata L. using 464.876W for 114.28 seconds. These findings underscore that MAE consistently outperforms traditional and enzyme-assisted methods in terms of efficiency and yield when optimized conditions are applied.

Table 2: Extraction of Anthocyanin using Microwave Assisted Extraction Technique

Material	Category	Conditions/Treatment	Findings of the work	References
Black Berry	Fruit	469W of microwave power, 52% solvent concentration, 25 gmL-1 of liquid-solid ratio, and 4 minutes of extraction time were all used.	Extraction yield of anthocyanin was (2.18±0.06 mg g−1).	Wen, Y., Chen, H., Zhou, X., Deng, Q., Zhao, Y., Zhao, C., and Gong, X. (2015)
Purple corn cob	Corn cob	1.5 M HCl and 95% ethanol, ethanol used as a solvent in ratio of 15:85 ratio with a cob: solvent ratio of 1:20 and a 400 W microwave power & extraction time was 10-30 min.	corn cob powder with a total anthocyanin content (TAC) of 397.1 mg/100 g.	Piyapanrungrueang, W., Chantrapornchai, W., Haruthaithanasan, V., Sukatta, U. and Aekatasanawan, C. (2016)
Lavandula pedunculata L. (well known Herb)	Herb	With a microwave irradiation time of 114.28 seconds, the solvent/sample ratio and microwave power were 30.321 (mL g-1) and 464.876 W, respectively.	the maximum yield for TAC (273.284 (mg L^{-1}) was obtained.	Farzaneh, V., and Carvalho, I. S. (2017)
Black Soybean (*Glycine max* L.) seed coat	Seed Coat	Ethanol concentration (59.99), a solvent to solids ratio of 40:1, an extraction duration of 262.54 seconds, and a power of 569.46 W.	5021.47 mg/l was the obtained yield.	Kumar, M., Dahuja, A., Sachdev, A., Kaur, C., Varghese, E., Saha, S., and Sairam, K. V. S. S. (2019)
Fruit of *Rubus coreanus* Maq.	Fruit	Microwave powder 148 W, microwave treatment time 1.10 min, and ethanol solvent content 74% (pH = 2)	Yield was obtained as 372.39 mg/100 g under the ideal extraction conditions.	Jiang HuaMei, Wang XiangQian, Yang Dan (2019)
Cockspur Coral extract	Flower Extract	microwave power of 300 W for 12 min,1:25 ratio of feedstock to solvent and a 300 W microwave power for 15 min.	Anthocyanin concentration (9.518 mg/L), maximum yield of anthocyanin, however, was only 4.091 mg/L respectively.	Astrilia Damayanti, Megawati Megawati, Laila Syafitri, LulukIsaroyati (2020)

Microwave assisted extraction of carotenoids

This study examined green extraction methods on antioxidants, polyphenols, and carotenoids in Cucurbita maxima pumpkins. Compared to conventional chemical extraction (CE), microwave-assisted extraction (MAE) with corn oil showed better carotenoid stability. MAE achieved high β-carotene yields from carrots (132.7 mg/100 g) and increased carotenoid yield in gac peel from 156 to 262 mg/100 g DW. Olive oil effectively extracted carotenoids from passion fruit peels (1178.54 μg in 25 minutes at 200W) and sea buckthorn pomace (28.3 mg/100 g oil). Optimal MAE conditions for muskmelon and watermelon shells were 400-500W, 0.5 mm particle size, and 120 seconds, yielding 590.85 and 474.72 μg/g of carotenoids. Flaxseed oil in MAE recovered 77.48% carotenoids from carrot juice. Adding oils can improve MAE efficiency.

Microwave assisted extraction of chlorophyll

Microwave-assisted extraction (MAE) and ultrasonic-assisted extraction (UAE) have proven highly effective for recovering carotenoids and chlorophylls from freshwater green algae. MAE yielded superior results compared to supercritical fluid extraction (SFE) and conventional methods, with higher carotenoid (5.21 mg/g) and chlorophyll (19.65 mg/g) recovery from Chlorella vulgaris. For Spirulina platensis, microwave pretreatment-assisted ethanol extraction (MPAEE) achieved a 1.27% chlorophyll yield, slightly higher than traditional methods. MAE also extracted chlorophyll more efficiently from filter mud and folium sauropi, achieving significant antioxidant activity. In pandan leaves, MAE provided high levels of antioxidant activity (2895.40 μmol/L), chlorophyll (12.72 μg/mL), and polyphenols (5.4 g/L).

Table 3: Extraction of carotenoids using Microwave assisted extraction technique

Material	Category	Conditions/Treatment	Findings of the work	References
Carrot (Leftover Waste)	Vegetable	7 minutes of MAE at 180 W/75 mL, 300 W/75 mL, and 300 W/150 mL	The maximum obtained yield was 112.6±10.1, 132.7±5.4, 122.5±3.5 and 110.9±9.5 mg/100 g (d.b.), respectively.	Bhudsawan Hiranvarachat, Sakamon Devahastin (2013)
Gac peel	Fruit	Ethyl acetate as solvent, Microwave power of 240W and 120W and extraction time of 4min, 6 & 10 min,25 min.	At 4 min, 156 to 236mg/100 g DW yield was obtained. At 240W yield obtained was 150 mg/100 g DW for 1 min & increased to 235 mg/100 g.At 25 min, the yield was 262mg/100 g DW.	Chuyen, HV, Nguyen, MH, Roach, PD, Golding, JB, Parks, SE. (2018)
Cantaloupes (Muskmelon& Watermelon)	Fruits	The ideal parameters for watermelon were 500 W, 0.5 mm, and 120 s, and 400 W, 0.5 mm, and 120 s for muskmelon shells.	Yield of carotenoids was found to be 590.85 µg/g for muskmelon and 474.72 µg/g for watermelon.	A. Brinda Lakshmi, J. Lakshmi Priya (**2018**)
Carrot Juice	Beverage/Drink	165 W of microwave power, 9.39 min of extraction time and 8.06:1 g/g of oil to waste ratio.	yield of carotenoid was 77.48%.	Aysel Elik, Derya Koçak Yanık, Fahrettin Göğüş, (2020)
Citrus Fruits	Fruits	68% hexane concentration, 561 W of microwave power, 7.64 min of irradiation, and 43 ml/g of solvent-to-solid using two successive extractions.	The yield obtained from maceration extraction (ME; 160.53 µg/g DM), Soxhlet extraction (SE; 162.68 µg/g DM), and MAE was 186.55 µg/g dry matter (DM).	Kadi, A., Boudries, H., Bachir-bey, M., Teffane, M., Taibi, A., Arroul, Y., and Boulekbache-Makhlouf, L. (2022) [57]
Chlorella biomass	Microalgae	hexane: acetone (1:1), & hexane: ethanol (7:3). For acetone optimum microwave power and time, 130 W and 1.69 min, for hexane extraction time was 1 min and microwave power of 100 W.	Acetone yielded 0.061 ± 0.003 mg/g of total carotenoids, hexane yielded 0.00173 ± 0.005 mg/g, and methanol yielded 0.0371 ± 0.004 mg/g.	Sarma, M.K., Saha, K., Choudhury, R., Pabbi, S., Madamwar, D. and Subudhi, S. (2022) [22]

Table 4: Extraction of Chlorophyll using Microwave assisted extraction technique

Material	Category	Condition/Treatment	Findings of the work	References
Spirulina platensis	Biomass	The parameters that were set were as follows: 60 seconds of radiation, 560 W of microwave power,52.8 minutes of extraction time, 55.1C of extraction temperature, and 10.8 mL/g of solvent to material ratio.	Chlorophyll yield using MAE obtained was 1.27%. and 0.12% by conventional method.	TONG, Y., GAO, L., XIAO, G. and PAN, X. (2012)
Filter mud	Agro-Industrial waste	An extraction liquid/solid ratio of 8:1 (mL/g), 40 °C extraction temperature, 50 s of microwave radiation, and 600 W of microwave power are required.	0.277 mg/g of chlorophyll (MAE in 60 minutes) & 0.259 mg/g chlorophyll yield (Conventional extraction in 240 min).	Guo, H. R., Ma, S. Y., Wang, X. F., Ren, E. F., and Li, Y. Y. (2012).
Folium Sauropi	Vegetable	acetone heated to 90 °C, 300W of microwave power, and a solid-to-solvent ratio of 1:30.	Chlorophyll yield Obtained was 14.430.16 g/mL.	Nguyen, N. H. K., Tien, H. T. C., Truc, T. T., and Quoc, L. T. (2020, December)
Pandans amaryllifoliusRoxb	Leaf	pandan powder: acetone ratio of 1:30, microwave power 300W, Extraction time of 2 minutes.	Chlorophyll a, b, and total chlorophyll content were respectively 9.4278 µg/mL, 4.2460 µg/mL, 13.6738 µg/mL, polyphenol content is 2.7577 g/L.	Nguyen, N. H. K., An, N. T. D., Anh, P. K., and Truc, T. T. (2021, July)
Moringa oleifera Lam	Leafy plant	solvent acetone 90°, solid to solvent ratio of 1:30, microwave power of 600W, and microwave-assisted extraction period of 2 minutes.	the chlorophyll content was 12.72±0.17 µg/mL, the polyphenol content was 5.4±0.09 g/L.	Nguyen, N. H. K., Chau, N. T. Q., Van Thinh, P., and Truc, T. T. (2021, April).
Chlorella vulgaris	Biomass	Temp. (40–60 °C), time (5–25 min), solvent–to–biomass ratio (20–90mLsolv/gbiom), and microwave power (300–800 watts).	63.36 mg/g_{extr} total chlorophylls yield was obtained.	Georgiopoulou, I., Tzima, S., Louli, V., and Magoulas, K. (2023)

Microwave assisted extraction of betalains, betaxanthin, betacyanins

Betalains are primarily extracted using solid-liquid methods, with water or ethanol/methanol solutions enhancing efficiency. A study compared a two-step microwave-assisted extraction (MAE) process at 400 W and 100% duty cycle with conventional extraction methods for beetroot betalains. The MAE process included adding L-ascorbic acid to prevent pigment degradation and a cooling phase to optimize pigment yield and stability. The highest betaxanthin concentrations (101.41 and 100.29 mg/100 g) were achieved with MAE at 400 W for 140 and 150 seconds. The best betalain levels (187.67±26.99 mg/100 g) were obtained with treatments involving 0.040 mol/L ascorbic acid for 130 seconds and 0.010 mol/L ascorbic acid for 100 seconds.

Table 5: Microwave assisted extraction of betalains, betaxanthin, betacyanins

Material	Category	Condition/treatment	Findings of the work	References
Beetroot	Root Vegetable	Extraction conditions as power (400, 800, and 1200 W), duty cycle (50, 100%), and time (0-160 s).	Yield of betalains was (187.67±26.99 mg/100 g red beetroot) and yield of betaxanthins was 125.43±21.75 mg/100 g red beetroot.	Cardoso-Ugarte, G. A., Sosa-Morales, M. E., Ballard, T., Liceaga, A., and San Martín-González, M. F. (2014))
G. globosa	globe amaranth	The optimum conditions for MAE (t = 8 min; T = 60 °C; Et = 0%; and S/L = 5 g/L).	Obtained yield of 39.6±1.8 mg/g dry weight.	Roriz, C. L., Barros, L., Prieto, M. A., Barreiro, M. F., Morales, P., and Ferreira, I. C. (2017)
Beetroot peels	Vegetable peel	For solvent A, the optimum conditions were pH 5.20, Microwave Power of 224.61MW, and Time 57.06 seconds & solvent B was pH 4.74, Microwave Power 384.25, Time 74.91 sec.	For solvent A, yield of Betanin was 229.264mg/ and for solvent B, Betanin yield was 472.113mg/L.	Singh, A., Ganesapillai, M., and Gnanasundaram, N. (2017) [31]
Amaranthus tricolour leaves	Leaf	For betacyanin conditions were 450W microwave power, 90 °C temperature, and 15 minutes & for betaxanthin: microwave power of 200 W, a temperature of 60 °C, and an extraction duration of 15 minutes.	The yield obtained for betacyanin was (71.95 mg/g of dw) and for betaxanthin was (42.30 mg/g dw).	Sharma, A., Mazumdar, B., and Keshav, A. (2021) [33]
Red dragon fruit	Fruit	Optimal conditions had solvent to material ratio of 1:30 (w/v), a temperature range of 60°C, a pH value of 2.25.	total yield of betacyanin was 0.4120 mg/100 g.	Saman, W., Mulyadi, A., and Wijana, S. (2023) [37]

Recent Trends in MAE Technology

Recent advancements in extraction technologies combine methods to enhance yield, selectivity, and efficiency. Integrating microwave-assisted extraction (MAE) with techniques such as osmotic dehydration, ultrasonication, freezing, vacuum, and infrared heating has proven effective. For example, ultrasonic-microwave-assisted extraction (UMAE) achieves a 97.4% pigment yield, outperforming traditional methods and ultrasonic extraction alone. This approach improves pigment extraction from paprika and other sources by damaging plant cells more effectively. Additionally, ultrasonic-microwave synergistic extraction (UMSE) from Eupatorium lindleyanum increased flavonoid yield by 2.46 times, reducing extraction time from 24 hours to 15 minutes and boosting pigment yield by 20.06%.

Reported Application of MAE Colouring pigments in food industry

Color is a key factor in a food product's acceptance, accounting for 62–90% of consumer judgment (Manzoor *et al*., 2021; Teixeira *et al*., 2022). Numerous studies have focused on microwave-assisted extraction (MAE) of natural pigments, such as anthocyanins, carotenoids, betalains, and chlorophyll, from various plant sources. Betalains have been effectively extracted from beetroot (Cardoso-Ugarte *et al*., 2014), and carotenoid-rich foods like carrot juice have shown promising results (Elik *et al*., 2020) [49]. Anthocyanins have been extracted from a wide range of plant parts, including berries, red cabbage, and saffron tepals.

Application of each pigment in food industry is given as follows:

Anthocyanin

Anthocyanins from plants have been used as food additives. E163, a food additive that is sold commercially, is derived from fruit anthocyanins, such as those present in grape skin. It's a purple food additive used to create purple beverages, candies, and jam. Concerns regarding the safety of synthetic food dyes and their detrimental effects on human health, particularly on neurological and behavioural functions, have recently been voiced by the public. (Azlan, A., Tang, S. T., Khoo, H. E., and Lim, S. M. (2017) [17]. There is a growing trend of anthocyanin-based colorants in some mixed fruit juices and yoghurt drinks. A few food manufacturers did use artificial coloring in their goods. Excessive consumption of these artificial colors may have negative effects.

Carotenoids

Carotenoids, known for their health benefits and antioxidant properties, are commonly used in food for coloring and nutritional enhancement. They contribute vibrant colors to fruits and vegetables—like β-carotene in yellow foods, lycopene in red fruits, and zeaxanthin in orange fruits. Zeaxanthin, in particular, is valued for its potent pigmentation abilities, often added to foods to achieve true color. Carotenoids are fat-soluble pigments found in fish, algae, fruits, and vegetables, and are also utilized in various food products as colorants and active ingredients.

Chlorophyll

Chlorophyll, a green pigment found in plants like nettles and peppermint, varies from dark to olive green. It is highly sensitive to pH, oxygen, temperature, and light, often turning brown in acidic conditions. Chlorophyll is soluble in oil and ethanol but not in water. There are two main types: chlorophyll a, which is green-blue, and chlorophyll b, which is yellow-green. It is used as a natural colorant in various food products such as beverages, jams, candies, and pickles.

Betalains

Betalains are being explored for their use as natural colorants, antioxidants, and antimicrobials. Studies have shown that red beet extract can be used in jelly and ice sherbets, providing a synthetic-like red color and enhancing product acceptability. Betalains also improve color stability in ice cream for up to 180 days at 20 °C. However, betalains from Rivina humilis used in banana juice and fruit spreads showed only 40% stability after six months at 5 °C. Additionally, betaxanthins from yellow pitaya have been used to color drinks and jelly candies.

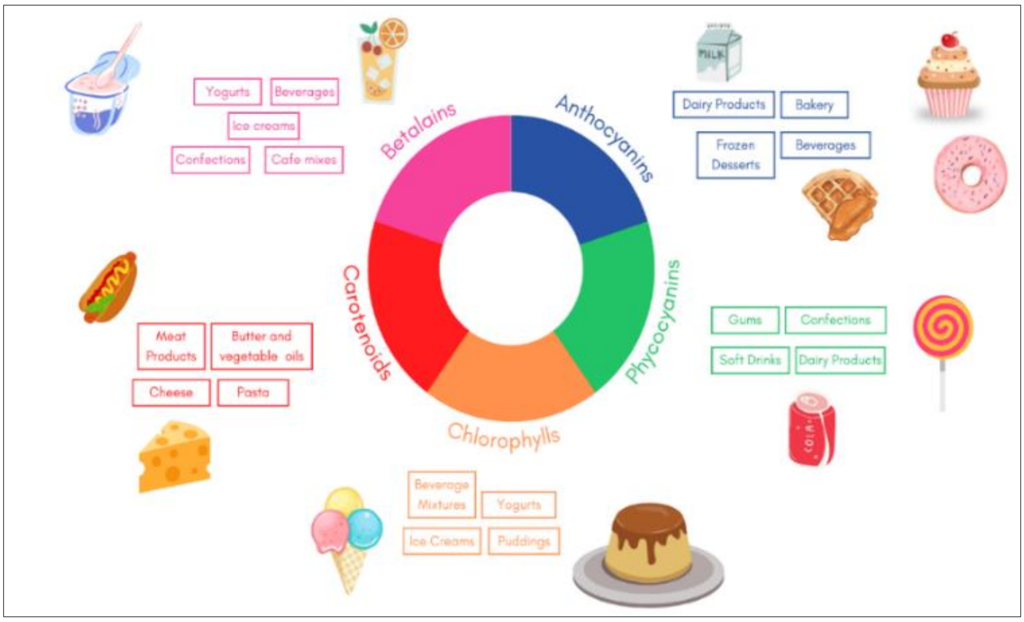

Fig 4: Application of Natural pigments In Food Industry

Research gaps and scope in future

As consumers become more health-conscious, there's growing demand for natural food colorants due to their health benefits compared to synthetic alternatives. Microwave-assisted extraction (MAE) is a promising, eco-friendly method for extracting natural pigments, offering higher efficiency, lower solvent use, and shorter extraction times than traditional methods. While MAE is widely used in food, pharmaceutical, and cosmetic industries, challenges remain, including pigment stability, industrial scalability, and the need for improved purification methods. Future research should focus on addressing these issues to enhance the quality and applicability of MAE-extracted pigments.

Conclusion

Extraction using microwave has been proven as a sustainable and non- conventional extraction method for extraction of natural pigments from various sources such as plants, microalgae sources, animals and many other sources. Due to the minimal solvent consumption, quick extraction times, and high extraction efficiency, this method is ideal for environmental detection, food inspection, and agricultural sample analysis. The mechanism or principle of MAE method has been designed in such a way that it is able to penetrate deep into tissues along with selective and heating which can be controlled. Despite of its numerous benefits and applications provided the various variables such as extraction time, solvent ratio, extraction time, microwave power need to be further optimised and investigated further to improve extraction efficiency at a large scale rather than only limiting to laboratory research and extraction analysis.

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