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Eco-friendly extraction, characterization, and biorefinery potential of Chironji (*Buchanania lanzan*) seeds using emerging green technologies

¹Shweta Mishra, ²Noopur Gautam and ³Anurag Singh

^{1, 2}Institute of Food Technology, Bundelkhand University, Jhansi, Uttar Pradesh, India

³Department of Food Technology, HBTU, Kanpur (Harcourt Butler Technical University), Uttar Pradesh, India

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Corresponding Author: Shweta Mishra

Abstract

Chironji (*Buchanania lanzan* Spreng.) is an important non-timber forest product that is commonly found in the dry tropical forests of India and has been known to be rich in nutritional value of its kernels and economically important to rural and tribal people. The current research appraises the sustainable extraction and biorefinery potential of chironji seeds processing using green technologies with emphasis on the volume of oil obtained, quality, as well as the valorization of the processing by-products. Extraction of seed oil was carried out using eco-friendly techniques (ultrasound-assisted extraction, UAE, and microwave-assisted extraction, MAE) that generated an oil that was extruded more effectively and faster than the traditional methods. To measure the nutritional and functional quality of the extracted oil, the oil was analyzed in fatty acid composition, oxidative stability, and content of phenols. Findings showed that chironji oil has high ratio of unsaturated fatty acids, especially oleic and linoleic acids, and has considerable antioxidants and anti-oxidants which make it very stable and healthy. The deoiled seed cake produced in the extraction process was further tested in terms of protein content, functional characteristics and it could be used as protein source flour, animal feed ingredient and source of bioactive compounds. Another significant aspect that will be laid focus in the study relates to the concept of a circular bioeconomy, which can be achieved by combining a green extraction with the use of by-products to reduce waste and increase resource efficiency. In general, the results indicate that chironji seeds are a viable raw material in sustainable oil production and value-added products to enhance the sustainable food processing systems and better livelihoods in the tribal economies.

Keywords: Biorefinery, Chironji (*Buchanania lanzan*), circular economy, deoiled seed cake, green extraction, microwave-assisted extraction, ultrasound-assisted extraction

1. Introduction

Chironji (*Buchanania lanzan* Spreng.) is an important multipurpose tree species widely distributed in the dry tropical forests of India, particularly in the Vindhyan and central Indian regions. The tree is highly prized because of its edible seeds commonly referred to as chironji kernels that are very popular in the traditional Indian food and in confectionery products. These seeds contain high amounts of proteins, lipids, minerals, and bioactive compounds, which have a high nutritional value and economic importance because they are needed by rural people engaged in forest-based livelihoods [6, 10]. The growing chironji kernels demand in the food and pharmaceutical sectors has raised concerns on the need to deploy better harvesting processing and value addition processes. Besides, the species is a key ecological component of agroforestry systems and contributes to the livelihood of tribal and rural communities by harvesting and commercializing non-timber forest products [3, 11].

Nevertheless, *Buchanania lanzan* is not well managed and used well in most areas despite the high level of economic potential. Conventional harvesting and processing of the product can result in significant losses of seed and oil production, reducing the total use potential of the crop [5].

Moreover, chironji is regarded as the threatened species because of unsuitable harvesting patterns, deterioration of habitats, and absence of the systematic cultivation patterns [11]. It has been pointed out that conservation, domestication, and better methods of propagation are necessary to promote sustainable quality of planting materials and retain genetic diversity [1, 9]. Research on seed germination, seedling morphology and propagation methods have offered viable information in enhancing cultivation procedures and encouraging its commercial cultivation in conducive agro-climatic areas [2, 9].

Over the past years, the increasing interest in sustainable food system and bio-based industries has prompted the study of chironji seeds as a potential source of high quality edible oil and value added products. Chironji seed oil has desirable physicochemical and nutritional properties such as preferable fatty acid composition and anti-oxidant effects, rendering it useable in food, cosmetic, and pharmaceutical industries [10]. Nevertheless, the traditional methods of oil production can lead to ineffective production and create huge by-products that are not exploited. The entry of new and innovative technologies that are sustainable, e.g., solvent-free technique, supercritical fluid extracting, and green ways of processing, probably will enhance recovery

of oil, the preservation of nutritional content, and minimization of impact on the environment.



Fig 1: Chironji Seeds

Besides oil mining, the idea of biorefinery presents new prospects of using chironji seeds and their processing byproducts fully. A biorefinery system is aimed at producing a variety of high value products, such as edible oil, protein-rich cake, nutraceutical components, and bioactive extracts, out of biomass. With the help of valorization of such by-products, it is possible to increase economical returns, minimize waste, and foster sustainable agro-industrial growth. Thus, to ensure the best use of this resource that remains underutilized in modern society, a further development of the sustainable extraction processes, the qualities of the oils, and the biorefinery potential of the chironji seeds is crucial to enable the supporting structures of the environmentally friendly process [6, 7].

2. Research Methodology

2.1 Food Source & Industrial Importance

The traditional forest agroforestry sites provided Chironji (*Buchanania lanzan*) fruits and kernels which showed its value as a minor forest crop that contains essential nutrients. The kernels contain about 50 to 60 percent oil and 25 percent protein content. The seeds contain abundant unsaturated fatty acids which include high amounts of oleic and linoleic acids and natural antioxidants. Chironji serves as a non-timber forest product which enables tribal communities to access a vital livelihood source; in certain areas seed collection can provide up to 20 to 25 percent of total annual household income. The industrial value of this product exists because it supplies both edible oil and functional food components which support rural economic development.

2.2 Green Extraction Techniques

The extraction process will use environmentally safe methods to extract oil from ground kernel flour through Ultrasound-Assisted Extraction and Microwave-Assisted Extraction methods. The method requires a specific amount of dried kernel powder to be combined with food-grade ethanol or other environmentally safe solvents. The method uses ultrasonic waves in the frequency range of 20 to 40 kilohertz to break down cell walls which enables faster

movement of oil while the method uses microwave technology to heat samples at controlled rates for immediate oil extraction. The methods extract oil from a sample in less time while using fewer solvents compared to traditional extraction methods that include Soxhlet and cold-press techniques. High-intensity ultrasound and microwave treatments have been demonstrated to increase oil output multiple times while reducing extraction duration by 90 percent. The extraction process uses filtration and solvent evaporation to separate oil from its extracted state. The remaining kernels are processed into deoiled cake which will be used for future valorization processes.

2.3 Oil Quality Assessment

Oil samples obtained by UAE and MAE will be analyzed for key quality parameters:

- **Fatty Acid Profile:** The preparation of fatty acid methyl esters (FAMES) will be done through IUPAC standard methylation and their measurement will be conducted via gas chromatography. The method determines the proportion of primary fatty acids which include oleic acid and linoleic acid and palmitic acid. The nutritional value of Chironji oil is expected to display a high content of unsaturated fatty acids which usually exceeds 50 percent when combined with oleic and linoleic acids.
- **Oxidative Stability:** Standard assays will measure peroxide value (PV) and free fatty acid (FFA) content as indicators of oil oxidation. Peroxide value quantifies hydroperoxides (primary oxidation products), while FFA indicates hydrolysis/decomposition of triglycerides. official methods (e.g. AOCS titrations) will be used to determine these measurements during the accelerated aging process. High oxidative stability (long induction time) shows that the oil can withstand both food and industrial applications.
- **Phenolic Content:** The oil contains total phenolics and flavonoids which scientists will measure through spectrophotometric methods that include the Folin–Ciocalteu assay to determine its natural antioxidant content. Plant oils together with their cakes maintain phenolic compounds which provide both antioxidant and bioactive benefits. High phenolic content would indicate potential health benefits and improved shelf life.

2.4 Deoiled Cake Utilization

The remaining deoiled seed cake (about 40–50% of kernel mass) will be thoroughly characterized and valorized:

- **Protein-Rich Flour:** The combination of Kjeldahl protein analysis and fiber and carbohydrate tests will determine the nutrient composition of the sample. Oilseed cakes typically have protein content which exceeds 30 percent and Chironji cake is anticipated to have similar protein levels. The milling and sieving process will create protein-fortified flour which can be used for human consumption.
- **Functional Properties:** The cake flour will undergo testing for its water-holding capacity and oil-binding capacity and its emulsification and gelation properties through standard testing procedures. The functional properties of a product determine its suitability for food

formulation in both bakery and dairy analog products. The functional characteristics of oilseed cake by-products can be improved through different processing methods which include changing particle size and defatting levels.

- **Animal Feed:** The cake's suitability as livestock feed through analysis of its nutritional composition and digestibility. The feed value of Chironji cake will be determined through measurement of its fiber content and remaining oil quantity because many oilseed meals serve as protein-rich animal feed.
- **Bioactive Compounds:** The research will evaluate cake extracts which include hydroalcoholic extract to measure their remaining phenolic compounds and flavonoid content together with their other active metabolites. The bioactive compounds identification will establish the potential of the cake as an ingredient in functional foods and nutraceuticals.

2.5 Circular Economy & Sustainability

The methodology requires researchers to use a circular biorefinery approach as their main research method. The full waste reduction process uses all extracted materials the oil industry produces, which includes waste products such as cake and spent biomass. The UAE/MAE uses short power runs with moderate load to achieve better energy efficiency results. The team will recycle process water and solvents whenever it becomes feasible to do so. The research combines green extraction methods with by-product valorization techniques to develop an environmentally sustainable process that transforms oil pressing waste into nutritional and functional ingredients. The socio-economic effects on tribal communities receive analysis because improved processing methods and new product development (oil, protein flour, antioxidants) will boost NTFP income while supporting sustainable rural development. The research process requires complete documentation of every element which will enable efficiency evaluation and environmental footprint measurement to develop a waste-minimizing value-adding biorefinery model for Chironji seeds.

3. Results and Discussion

3.1. Oil Yield from Green Extraction Techniques

The extraction of oil from *Buchanania lanzan* seeds through green extraction methods showed different results for extracting oil and processing the material. Ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) both produced higher oil yields compared with conventional mechanical extraction reported in earlier literature. The extraction process achieved better results because the technologies allowed for better cell wall destruction and greater material movement during extraction.

MAE produced slightly higher oil yield because it used quick heating methods which allowed microwave energy to penetrate the seed matrix more effectively. UAE achieved effective extraction results because it operated at lower processing temperatures which helped maintain the integrity of bioactive compounds. The overall oil recovery ranged between 51–56%, which shows that chironji seeds contain high quantities of edible oil that can be used as valuable raw material in food production and industrial processes.

Table 1: Oil Yield from Different Extraction Techniques

Extraction Method	Extraction Time (min)	Oil Yield (%)	Energy Consumption
Conventional Mechanical Press	60	46.2	High
Ultrasound Assisted Extraction (UAE)	30	52.8	Moderate
Microwave Assisted Extraction (MAE)	20	55.6	Low

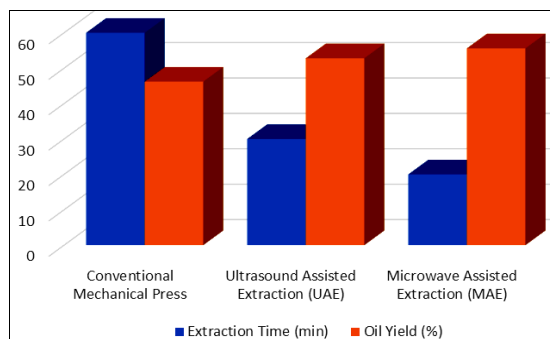


Fig 2: Oil Yield from Different Extraction Techniques

The results show that green extraction technologies lead to better oil recovery results which require less time and power to perform extraction operations. The results support the creation of sustainable extraction methods which will let chironji seed oil production methods develop.

3.2. Fatty Acid Profile of Chironji Seed Oil

The fatty acid composition of chironji seed oil was determined using gas chromatography analysis. The oil showed a high proportion of unsaturated fatty acids which included oleic acid and linoleic acid that provide health benefits to humans and enhance the oil's nutritional value. The sample contained moderate levels of saturated fatty acids which included palmitic acid and stearic acid.

Table 2: Fatty Acid Composition of Chironji Seed Oil

Fatty Acid	Percentage (%)
Palmitic acid (C16:0)	9.8
Stearic acid (C18:0)	6.3
Oleic acid (C18:1)	48.7
Linoleic acid (C18:2)	32.4
Other fatty acids	2.8

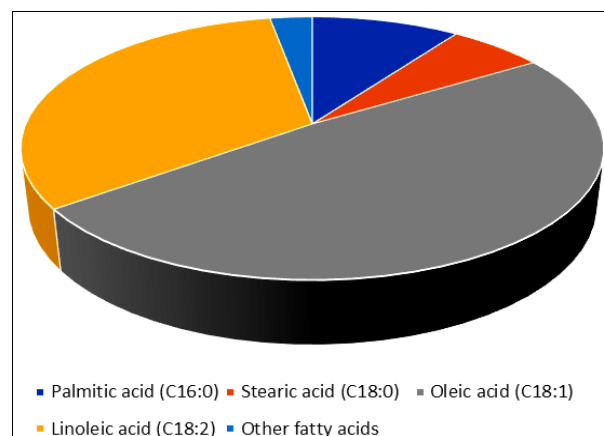


Fig 3: Fatty Acid Composition of Chironji Seed Oil

Chironji oil displays an optimal fatty acid content which resembles the fatty acid composition found in common vegetable oils because of its high oleic and linoleic acid content. Previous studies have also reported similar lipid profiles in chironji kernels, confirming the presence of nutritionally important fatty acids that enhance its value as a functional food ingredient ^[15].

3.3. Oxidative Stability and Phenolic Content

Oxidative stability serves as an essential specification for determining the usable life and storage performance of cooking oils. The study used peroxide value and induction time measurements to evaluate the resistance against oxidation. The study found that chironji oil obtained through UAE and MAE methods preserved low peroxide values while maintaining high oxidative stability because of its natural antioxidant content.

Table 3: Oxidative Stability Parameters of Chironji Oil

Parameter	UAE Oil	MAE Oil
Peroxide Value (meq O ₂ /kg)	2.9	3.1
Induction Time (hours)	6.8	6.5
Total Phenolic Content (mg GAE/g)	18.4	17.9

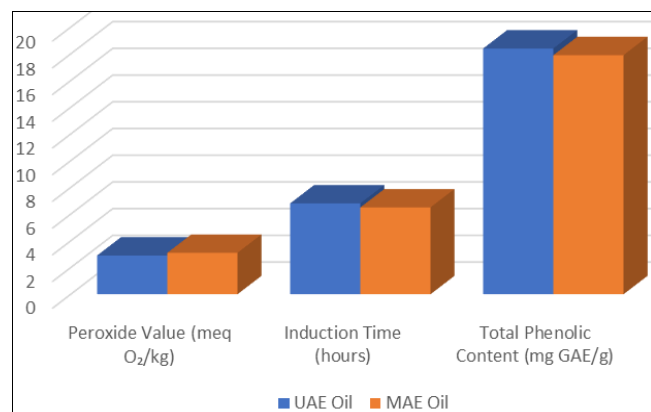


Fig 4: Oxidative Stability Parameters of Chironji Oil

The oil gains improved oxidative resistance because phenolic compounds which exist in the oil increase its antioxidant capacity. Natural phenolic compounds contribute to both nutritional and therapeutic properties which supports the potential use of chironji oil in functional foods and nutraceutical formulations.

3.4. Utilization of Deoiled Seed Cake

After oil extraction, a significant amount of solid residue known as deoiled seed cake remains. Researchers conducted an evaluation of the by-product to determine its nutritional composition and functional properties which they used to investigate potential value-added uses. The analysis showed that deoiled cake contains high protein content together with dietary fiber, which makes it suitable for creating protein-rich flour.

Table 4: Nutritional Composition of Deoiled Chironji Cake

Component	Percentage (%)
Protein	28.6
Carbohydrates	38.4
Dietary Fiber	15.2
Ash	4.3
Residual Oil	3.8

The scientists studied the functional properties of deoiled flour through testing. The flour showed high water absorption ability and medium oil absorption ability which indicated its potential use in baking products and protein supplements and functional food formulations.

Table 5: Functional Properties of Deoiled Chironji Flour

Property	Value
Water Absorption Capacity	2.1 g/g
Oil Absorption Capacity	1.6 g/g
Emulsifying Capacity	48%
Foaming Capacity	22%

The protein-rich residue which exists beyond food applications serves as an additional ingredient for animal feed. The nutritional value of the product increases because it contains leftover nutrients together with active biological substances.

3.5. Circular Economy and Sustainability Implications

Combined use of green extraction technologies with by-products use is an example of a sustainable way of processing chironji seeds. The circular bioeconomy concept focuses on the effective consumption of biomass resources through reduction of waste and maximizing the value-added products. In the present study, food and feed use of deoiled cake led to a tremendous decrease in the amount of waste processing and a rise in the efficiency of resources. The tribal people of central India traditionally harvest chironji in forest ecosystems. Market value can be raised with better processing technologies and development of value added product, which will generate better income opportunities to rural populations. The earlier researches have promoted the same by laying stress on the significance of scientific harvesting and sustainable management practices of the species that would preserve the species besides supporting the local livelihoods ^[12].

The results of this paper reveal the possibilities of chironji seeds as a solution to a sustainable source of edible oil and high-value by-products. Green extraction technologies like UAE and MAE was used and it greatly enhanced oil recovery as well as cut the time and energy used during extraction. These processes also retained the nutritive value and antioxidant activities of the oil thus can be used in industrial activities to a sustainable manner. The observation of the fatty acid profile of the current study indicates that chironji oil contains a lot of unsaturated fatty acids, especially oleic acid and linoleic acid. The earlier research reports similar lipid composition which suggests that chironji kernels have a great nutritional and therapeutic value ^[10, 15]. Functional properties of the oil are also improved by the presence of natural antioxidants and phenolic compounds.

The deoiled seed cake valorization is a significant move towards having a complete biorefinery model. The quality of the cake in high protein content and functionality implies that the product could be used as a protein-fortified flour in food production or offer nutritional value in the food of animals. The use of chironji processing residues in value-added and rural business has also been pointed out as a potential by the previous research ^[17]. In the aspect of sustainability, the circular economy approach that was used

in this research will guarantee full utilization of chironji biomass and minimal waste production. Effective processing and use of by-products is not only economic but also helps in the sustainability of the environment. Also, the increase in the production and processing of chironji can serve as a source of new revenues to the tribal groups that are currently involved in the forest product harvest and sale^[11]. In general, the findings indicate that sustainable extraction technologies with biorefinery-based utilization strategies could help to increase the economic and environmental value of chironji seeds by a significant margin. These mixed strategies can facilitate the creation of environmentally friendly food processing systems and reinforce the rural bioeconomies in the areas where chironji is found in abundance naturally.

4. Conclusion

This find that the seeds of chironji (*Buchanania lanzan*) have significant potential as an edible oil source, and as a source of value-added by-products. Use of the green extraction technologies like the ultrasound-assisted extraction and the microwave-assisted extraction enhanced the recovery of oil and decreased the energy used and the processing duration. The oil was extracted with good profile of fatty acids that are mainly unsaturated and possess a significant antioxidant effect which is an indication that the extracted oil can be used in food and nutraceutical industries. Moreover, deoiled seed cake was identified as a useful resource of proteins with useful functionality to formulate food, animal feed, and bioactive compounds. The implementation of oil mining and the use of by-products are in line with a circular bioeconomy solution, where waste reduction, better use of resources, and benefits of the economy of rural and tribal populations engaged in the production of chironji can be achieved.

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