Systematic Analysis of Neem Seed Extraction Machinery: Design, Performance, and Applications

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Abstract— **In the current review, the development of mechanical mechanisms of extracting neem seed oil is critically discussed. Starting with manual presses the story continues with the introduction of automated hydraulic and screw-based presses, giving special attention to mechanical pressing, seed pre-conditioning and filtration measures that can yield as much as 57%. Hydraulic presses are emphasized as a cheap solution to small-holder farmers, but expeller systems, though faced with solvent sometimes-by-products and requiring more capital, show better business ability. The application ranges its applications to on-farm treatment, biopesticides of biochemical nature that are more sustainable than synthetic chemical ones, the assistance of the creation of medicines, and the production of biofuels are also discussed systematically. The main identified challenges are photodegradation which reduces the efficacy of the neem oil, the challenge of analysing a product, the mechanical challenges posed by the abrasiveness of the neem seeds, and the initial high cost of the product to rural users. Future research options are also presented, which recommend extraction assisted with ultrasound and microwave, real-time optimisation by incorporating AI and IoT, the use of blockchain to track, and the use of non-conventional solvents, including deep-electrolytic solvents (DES). An integrated paradigm based on low-cost and solar-powered presses with ultrasonic and internet technologies is predicted to make small farms more efficient by 2030-35, minimize material waste, and enable building circular economies in the Global South.**

Keywords*— *Agricultural sustainability, Azadirachtin, Biopesticides, IoT, Mechanical press, Neem oil.

I. INTRODUCTION

Neem Azadirachta indica or neem (also known as Azadirachta indica), belonging to the family Meliaceae is an evergreen shrub, which grows very fast) and has its native in the Indian subcontinent Over two millennia it has been intentionally domesticated since the tropical, subtropical, and temperate parts of Asia, Africa, the Americas and Europe. The salutary influences of age-old medical monographs, are testified by the maxim, that Spurica promotes good health. In accordance each of the plant organs has been harvested and converted, root, bole, bark, leaves, flowers, fruits, and seeds, to both therapeutic and industrial purposes[1]. The maximum yield of 44.141410 is obtained using the n-hexane in a Soxhlet apparatus at the particle size of 0.212mm, a temperature of 64.416 and a residence time of 132.677 min with a high oil content of 25 -45 by weight. Following thermodynamic analysis reveals that the recovery of oil is maximized with increase in dwell time and temperature; but that the reduction in the diameter of particulate matter only maximizes production reaching to 54.14 per cent at 0.5 mm, 55 C and 150 minutes[2].

The general characteristics of neem seed oil include a density of 0.875 g cm^{-3}, a viscosity of 33.5 $mm^2 s^{-1}$, a specific gravity of 0.88, a saponification value of 206.7 mg KOH g^{-1}, an iodine value of 122.5 g I_2 per 100 g, an acid value of 1.81 mg KOH g^{-1}, and a high cetane number of 75. It has a fatty acid profile dominated by oleic acid (60.9), palmitic acid (22.4), and caprylic acid (16.6), supplemented by bioactive components including azadirachtin, salannin, nimbi Din, gedunin, nimbolide, and a range of limonoids and this contributes to its antifungal, antibacterial, antiviral, antioxidant and pesticidal properties[3].

These properties make neem oil a biodegradable and environmental harmless alternative to synthetic chemicals. It serves as a bioinsecticide and bioherbicide, blocking the insect melting process, repelling Odors, retarding the growth of fungi and protecting beneficial non-targeted organisms. Its medicinal effect includes possible treatment of diabetes, tuberculosis, hypertension, different cancers, malaria, eczema, and cutaneous infections, which is affected by anti-inflammatory, hepatoprotective, and antioxidant mechanisms. In cosmetic product it is used in soaps, creams and facial masks, whereas in the food industry, it is used as a natural preservative; and industrially it is incorporated into lubricants, leather protectors, pharmaceutical carriers as well as in epoxy resin precursors. Mechanical pressing is less desirable when compared to soxhlet extraction with hexane as it has less recoveries, higher turbidity, and is less economical at a larger scale.

Regardless of this promise, manual methods that are considered low in technology such as hand pressing, pestle grinding, etc, are still very common[4]. The inefficiencies, labour-consuming tediousness, loss of seeds and poor quality of oil. incur such practices. The growing world demand of the products derived out of neem require mechanised neem extracting devices including expellers, hydraulic press, and screw press, to improve efficiency, preserve bioactivity, increase production capacities and reduce the labour-intensive elements. Figure1 illustrating overall process flow of neem seed oil extraction

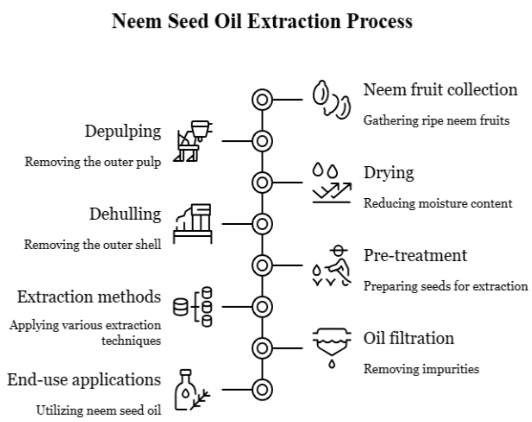

Fig.1. Overall process of neem oil

A. Importance of Neem Seeds and Neem Oil

Azadirachta indica (neem) has been demonstrated to possess outstanding antimicrobial, antioxidant, and pesticidal properties, primarily attributed to the oil extracted from its seeds. The oil content of neem seeds is reported to range between 25–45% (w/w). Soxhlet extraction using n-hexane at an optimal temperature of 64.4 °C, a particle size of 0.212 mm, and an extraction time of 132.7 min yields a maximum oil recovery of 44.14%. The physicochemical properties of neem seed oil-namely, a density of 0.875 g cm^{-3}, viscosity of 33.5 mm^2 s^{-1}, specific gravity of 0.88, saponification value of 206.7 mg KOH g^{-1}, iodine value of 122.5 g I_2 100 g^{-1}, acid value of 1.81 mg KOH g^{-1}, and a high cetane number of 75 - indicate its suitability for applications in biofuels, lubricants, and other industrial sectors[5].

Dominant fatty acids include oleic, palmitic and caprylic, which are supplemented by bioactive limonoids, which include azadirachtin, salannin, nimbidin, gedunin, nimbin and nimbolide and are the basis of its therapeutic and agricultural activity[6]. It is known to disrupt insect melting, deter pests, suppress fungal proliferation, display anti-inflammatory, hepatoprotective, and antioxidant effects and proving to be harmless to valuable species. Neem oil is used clinically in the prescription of diabetes, tuberculosis, hypertension, cancer, malaria, eczematous and infections. Medical uses are in skin moisturization, microbial control of soaps and lotions, and industry use includes preservation of leather, promotion of drug delivery, and production of epoxy resins.

The size, density, hardness of the seeds are physical properties that influence the mechanism of crushing and flow processes of the scalp in mechanised systems. Although solvent extraction does not yield and extract better than mechanical pressing., the classical methods are still being used. thus, supporting the idea of mechanised production methods that are sustainable to satisfy the increased demand of neem products[7].

B. Applications in Agriculture, Medicine, Cosmetics, and Bio-pesticides

The extracts of oil of Azadirachta indica and its individual extracts have found a large niche in agricultural practice in the form of powerful bioinsecticides, so that the manufacturers are able to go to massively decrease the use of traditional and typically harmful insecticides in the form of sprays. An example of such a compound is azadirachtin, which has been identified as the key active ingredient that interrupts the hormonal activation of insects and, in that way, hinders the process of melting and feeding and does not affect non-target insects, including ladybirds and pollinators[5]. Practically, however, the agro-farmers include azadirachtin into a dust matters or spray applications to handle a broad range of phytophagous pests such as locusts, aphids and coleoptera's species which in many cases have been demonstrated to have demonstrable effectiveness in organic farm production systems where synthetic alternatives are still not allowed. In its improper applications, in addition to its insecticidal effects, neem oil is also a bio fungicide of the foliar blight and mildew, and an insecticide that can be used bioherbically to inhibit the growth of unwanted weeds like Senna occidentalis.

In the sphere of humankind health neem oil is highly packed with antioxidant and anti-inflammatory ingredients which were already proven over the ages, centuries by the herbal experts. Modern studies indicate its future application in the improvement of metabolism disorders like diabetes through glycaemic control, in the treatment of tuberculosis through antibacterial effects, in the treatment of hypertension and in the treatment of more challenging diseases like oncological cancer and malaria infections. In dermatological cases, eczema, as well as boils and other cutaneous infections, the salannin and nimbin compounds of the substance have a calming effect and acting as antimicrobials to do so with no adverse side-effects of a steroid-treatment[2].

The cosmetic sector also takes advantage of the multifunctionality of neem where it is used in soaps, lotions, shampoos and formula on the face to produce a myriad effect of deep but at the same time hydrating effect. Its antimicrobial effects work against the acnes causing bacteria, dandruff causing fungi as well as scaled up conditions of the scalp but on the other hand it also gives the softening effect to the integumentary system. Regarding the further perspective of the development of bio-pesticides, neem shows significant potential due to its sustainable low-residue formulations which protect crops productivity, and maintain the ecological integrity that would correspond to the international trends in developing more friendly pest management principles. Together, these features make neem a constantly useful product in many applications in the fields of agronomy, on the one hand, up to the production of pharmaceuticals, on the other hand.

C. Need for Mechanized Neem Seed Extraction

The growing demand in the world market of neem-based products and the inefficiency of the standard expansion methods make a need to adopt mechanisation so as to increase the oil extraction at the same time improving the efficiency of the entire process. Nevertheless, in its manual mode, neem seeds can produce oil of only 25-45 percent weight but the traditional form of crushing only one-fourth of the potential, which often causes seed scalding and the formation of creamy, inferior quality oil mixed with extraneous impurities. Farmers and small-scale processors also suffer extended physical efforts and leads to the lower nature of productivity whereas their products yield significantly low when compared with solvent extraction processes like the Soxhlet which can reach up to 44 per cent under ideal conditions *(64 °C extraction temperature and 0.2 mm particle size)*. The neem rising prominence compels the imperative to mechanise. Aza-enriched bio-pesticides are also effective in deterring aphids as well as locusts without harming desirable arthropods thus leading to the acceptance of the practice by organic farming communities across the globe[8]. At the same time, antidiabetic, antifungal, and anti-malarial activities are also applied in nutraceuticals, and as soon as solid data on the therapeutic indices is obtained, market acceptance will increase too. On the one hand, manufacturers of cosmetic products use neem derivatives in their recipes that provide antimicrobial protection in addition to offering hydration and antioxidant properties. Besides, such industries as leather conservation and biofuel manufacturing are also flocked to the neem oil with good cetane number of 75, which further solidifies its role in the bioproduct chains of high values. Demand of such alternatives that are environmentally friendly is exceeding supply; India alone produces millions of tonnes of neem seeds annually and only a fraction of these seeds is being wasted because of an out-dated technology in extracting them.

The possible solution is mechanisation through expellers and hydraulic presses and screw-type forms. These technologies can enhance throughput up to 100 times, can eliminate labour requirement by up to 80 percent and can preserve volatile bioactive compounds e.g. nimbin and salannin which would otherwise be destroyed by manual processing[9]. Maximisation of design considerations to fit the non-uniform hardness and density characteristics of neem, design efficiency can be brought to near those of solvent extraction however without hexane contamination. Although the smallholders might be inhibited by the initial capital investment, the aspect of scalability provided by the mechanised solutions results in higher purity of oils that can be offered at premium prices and as such reduce labour costs and reduction in wastes. Empirical evidence supports that in favourable conditions extractions by use of expellers yield 3040 percent and any additional increase can be secured through the application of barrel-based heat processes that lead to increased lipid mobilisation. Mechanisation is therefore more of a necessity than an upgrade, as not only is it a key to sustainable large-scale production of neem to satisfy farming, pharmaceutical and ecological needs, but also, human labour and ecological integrity will remain unharmed[10], Figure 2 presents a conceptual overview of the neem tree, highlighting its multifaceted importance across cultural, technological, and sustainability dimensions.

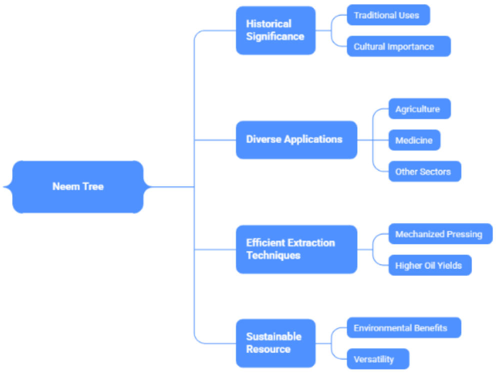

Fig.2. Conceptual overview of the neem tree

II. NEEM SEED CHARACTERISTICS AND OIL PROPERTIES

Neem seeds include the properties necessary to extract the maximum amount of oil, and it is necessary to gain a clear insight into their physical properties and chemical composition to the advantage of both machine designers and process engineers. They are small, oval, kernels of about 1-2cm long, and they have a strong exocarp that is densities of around 0.6-0.8gcm -1 and hardness levels that require a lot of crushing power[11], [12], [13]. The hardness of this shell makes it hard to crush using manual power and this would take long and use a lot of labour yet it yields only little and leaves a sticky end product. Chemically, the seed matrix consists of 2545 per cent oil, mostly oleic and palmitic acids, as well as a range of biologically active triterpenoids, including azadirachtin, nimbin, and salannin, which give the seed matrix its characteristic pest-resistant properties. However, as far as these bioactive are concerned, exhaustive recovery without impairing them is difficult. Over thermal input causes destruction of the active constituents, and very fine comminution causes equipment to become fouled. Leveraging the Soxhlet extraction, which delivers yields of over 40 percent at 60 C with hexane; mechanical press system designs must be designed intelligently to replicate this can be seen with careful design changes that will reduce the need to use solvents. The design (modification) of machinery to match the seed size to allow efficient hopper processing, density to achieve maximum flow, and the oil viscosity to meet barrel design would eventually achieve higher recovery, purity of products and scale, thus sustainable profitability to stakeholders[13].

A. *Physical and Mechanical Properties of Neem Seeds*

The characteristics mentioned above size, shape, density, and hardness have a significant influence on determining the design constraints of efficient extraction system, which, in turn, include crushing force requirements and the dynamics of material flow among others. Neem seeds are typically small, oval kernels and measure about 120cm long, 78135cm wide and thin. These measurements are caused by drying up of the de-pulped fruits, which makes it easier to separate the kernel and the hard outer cover. The owing to its irregular oval shape mostly tapering towards the top and rounded at the bottom, the shape has an effect on the bulk handling properties in a hopper and conveyor. Seeds with aspect ratio of approximately 1.5: 1 length-to- width are likely to interlock and hence result in bridging in thin hoppers unless specially designed to move freely by suitable angle settings in hoppers of 60-70 degrees with vibratory support

Another important parameter is density. The true density of neem seeds lies between 0.6 and 0.8 g cm^{-3}, while the bulk density ranges from 0.4 to 0.6 g cm^{-3}, depending on varietal differences and moisture content. These values are lower than those of most conventional oilseeds, such as sunflower seeds (approximately 0.9 g cm^{-3}). The lower density implies a reduced mass per unit volume, necessitating larger hopper capacities and modified screw volumes in expeller plants to maintain constant feed rates. In addition, the porosity of the seed bed (40–50%) is relatively high, which significantly affects compressibility during the pressing process. Increased void space reduces effective pressure buildup, potentially leading to poor oil yields unless a pre-compression stage is incorporated into the press design[12].

Hardness is the most important mechanical characteristic: neem seed shells have compressive strengths of 1020 Mpa and have a hardness of about 34 the Mohs scale, which is similar to almond shells. Rupture of these shells will require large crushing forces; manual crushing can usually only partially crush a shell, and mechanical presses are required to have a torque greater than 50NM and a pressure at the barrel of 20-40 Mpa in order to rupture a shell with a minimum amount of wear. The resistance of abrasion is average, thus the friction coefficients guide the selection of materials, as an example when the manufacturer employs hardened steel or components of nitrided alloys, it decreases downtime. Other characteristics such as angle of repose, which suggests a medium flowability, and sphericity that determines the size of sizable sieves in the cleaning process are also critical.

All this easily translates into engineering requirements; the size of the seeds determines the size of the hopper aperture and screen size to prevent blockages; the shape and density of seeds determine the screw pitch, i.e. 10-15mm, and the flight clearance, 1-2mm, to provide free, axial, flow. The control of press configuration is dictated by the hardness: batch hardness of up to 100Mpa can be provided by hydraulic systems, and tapered barrels with a 2030 bias degree can be used to continuously compress, providing progressive compression. To facilitate the design of energy efficiency, pressure gradient is foreseen through the usage of a Darcy-Weisbach equation. Prior roasting of between 60 and 80 Degree Celsius would reharden the shell by 2030 per cent which existing in softening the kernels and increasing the yield to 35-40 per cent[11].

The inability to consider these parameters leads to waste in the operation of the machines: They will have oversized hoppers that spend more time in unnecessary space, under screwed screws that generate less than 25 percent yields, and the lack of optimal operation will cause uneven pressure. The maximal efficiencies of optimised machinery, calibrated to the above metrics, can reach 80% - efficiencies of solvent techniques, without the usage of chemistry. Table 1 provides a brief overview of the key properties with the design implications.

Table 1. Overview of properties with design application

Property	Typical Value	Design Impact
Size (L×W×T)	1-2 × 0.8-1.5 × 0.5-1 cm	Hopper size, screen mesh (0.5-2 mm)
Bulk Density	0.4-0.6 g/cm³	Feed rate, screw volume
True Density	0.6-0.8 g/cm³	Compressibility, porosity (40-50%)
Hardness	10-20 MPa	Crushing force (>20 MPa), material (steel)
Moisture	8-12%	Pre-heating, anti-clogging
Angle of Repose	28-35°	Hopper angle (>60°)

Fundamentally, the evolution of the extraction technology with reference to the physical-mechanical properties of the neem seeds is a strategic milestone towards breaking the traditional limits, which successively allowed the extraction of oil at large scale through an ecologically industrial process[11].

B. Oil Composition and Extraction Challenges

Intended fatty acids as well as diverse triterpenoids found in neem oil contribute to a complex molecular composition which forces anything willing to extract it. Accordingly, the usage of techniques should not be a destructive method to maintain the molecular integrity and bioactivity. Neem seeds normally contain 25 -45 percent oil which is a greasy brownish material that is mainly made up of unsaturated and saturated fatty acids. Oleic acid provides 40-60% of the total, which provides the ability to remain soft, but palmitic and stearic acids are the determinants of firmness; coconut oil is necessary to be active in the body. Compositional qualities such as these, which are supported by GC -MS examinations of green -solvent extractions (e.g., ultrasound, or microwave-assisted extraction with acetone/isopropanol), compete with edible oils in quality but require low -temperature treatment to prevent the formation of rancidity[14].

The bioactive triterpenoids- mostly azadirachtin, nimbin, salannin, and gedunin- make 0.2-3 per cent of the total make up, and are found particularly in the kernels. They are thermally labile (degrade above 60° C) polar limonoids, making their recovery difficult using non-polar solvents like hexane in Soxhlet boiling using the effect of solvents method, which commonly gives a recovery of over 40 o C in hexane. Mechanical pressing also exists, but exposes the cake to oxidation risks by fines and frictional heat, leaving 510per cent of azadirachtin in the cake as compared to losses with solvents.

Difficulties are magnified by seed characteristics: the shell hardness will inhibit rupture of the kernel, expeller tendency will obstruct running, and the abundance of free fatty acids will hasten the hydrolysis process[15]. The highest pretreatments of the phenols (that is, roasting) at 55 -80 C in ten minutes or comprehensive grinding can increase the yields by 20-30 percent without causing degradation. The purification of mechanical processes to be similar efficiency of Soxhlet extraction requires the presence of cooled barrels, fine sieves and re-pressing in a combination between hybrids. To create a balance between recovery, purity, and bioactivity is also necessary towards the sustainable use of neem as a pesticidal and cosmetic resource.

III. TYPES OF NEEM SEED EXTRACTION MACHINES

The consideration of the various methods used in the extraction of the neem oil is crucial in understanding the trend in terms of technological advancements that have slowly shifted into simple manual techniques of extracting its oil all the way to advanced automated process.

A. Standard/Manual Extraction Processes.

These methods, often defined by their low efficiency and the high level of human effort, include primitive methods like hand pressing, pestle-mortar grinding or crudely made lever presses. Hand pressing: This is done by forcing the dehulled neem kernels between wooden blocks or stones. The technique, which is common in agrarian communities of India and Africa where neem trees are widespread, is solely applicable to human labour. The yields are usually 5-15% due to the application of varying degrees of pressure and incomplete expression of oil due to the resistance posed by the levels of hardness of the shells of the hard seeds, which has a hardness 10-20 Mpa without mechanical aid. It is also home fabricable, but extremely labour-intensive, consuming 4-6 hrs/kg of seed, and is again susceptible to contamination as a result of human touch[16].

Pestle and mortar grinding used in rural areas involves crushing dry neem seeds in a mortar made of stone in order to crack the kernels, and then grinding or squeezing them by hand or by means of a simple cloth. Though grinding raises the amount of surface area where oil is released, it generates fines that block fabrics, leading to a yield of 10-20 based on the oil, but large amounts of the material are wasted to the press cake[15]. With some marginal progress in recovery, pre-treatments such as sun-drying to 8-12 heat content, roasting that reduce shells softness by 20-30 percent yield benefits, though the cure of microbial contaminations is still possible where hygienic conditions fail. Choosing an appropriate hardening of tools is necessary to avoid wear as the modern material science requires.

Simple lever presses are an intermediate development, using rams made of wood or driven by animals. These exert forces of 5–10 MPa, which are inadequate to achieve high yields, typically less than 25 percent, when compared to mechanical systems that have the capacity of producing 20–40 MPa when using a system of driving forces. Their size is still small enough to be carried by smallholders; they are also slow, at 1–2 kg h^{-1}, with variable compression, which lowers throughput and area of work. Although these are disadvantages, the manual techniques do not require any chemicals and are thus free from effects on bioactive compounds such as azadirachtin, which is used as a pesticide and cannot be replaced. Such a shift might still leave cultural heritage intact, but will emphasize the necessity of alternative options that should be scaled[17].

B. Mechanical Expeller-Based Systems

Although in some cases work by hand is still done, some form of mechanical expeller is an evolutionary move, which uses a sustained screw press to maximize oil recoveries and throughput of neem seeds. Such machines utilize a powerful helical screw that rotates in a perforated cylindrical barrel, in which rotating flights sequentially squeeze dehulled or pre-crushed seeds against tapered restrictions, creating pressures of 20–50 MPa that rupture the oil-bearing cells and eject oil through narrow openings, often 0.5 - 1 mm wide. The screw pitch reduces gradually along the length, feeding generously at the inlet end and reducing at the outlet end to provide greater squeezing power, pump axial flow, and reduce slippage—an important transformation to meet the irregular geometry and bulk density of neem of 0.4 - 0.6 g cm^{-3}[18].

Oil flows through barrel holes into a collection tank and is separated by gravity or centrifugal filtration to extract 25–40% oil by weight of seed, which is far greater than the 5–20% retrieved by manual methods. By 20–30%, controlled thermal degradation of lignin to soften shells through pre-treatments such as sun-drying to 8–12 percent moisture and roasting at 60–80 °C exposes kernels to subsequent increases in yield. The system is driven at 20–50 rpm by electric motors with gearboxes to provide torque magnification to overcome the hardness of the neem shell, using hardened steel or nitrided alloys to resist abrasion[19].

Scalability, reduced labour, and bioactive conservation (as mechanical pressing does not require the use of solvents) are the benefits of this method. However, issues still persist: initial fines due to brittle shells clogging the screens, necessitating vibratory cleaners; excessive heat may cause degradation of limonoids, which can be prevented by water jackets; the press cake retains 5–10% residual oil, and recovery is achieved through re-pressing or solvent extraction. With average energy consumption of 20–40 kWh t^{-1}, its energy efficiency is competitive with hydraulic systems, while being far more continuous in operation[8], [18].

Smaller models, including Indian designs with capacities of 50 kg h^{-1}, are appropriate for rural cooperatives, while larger models incorporate preheaters and auto-feeders, achieving efficiencies comparable to solvent extraction. Darcy–Weisbach principles have been applied to define material flow through pressure-gradient calculations that enable homogeneous expulsion of material from the machine. To conclude, expeller systems democratize neem oil production, bridging the gap between traditional and mechanical methods and enabling sustainable production of this high-value commodity crop[8].

C. Hydraulic and Screw Press Mechanisms

Hydraulic presses operate under a hydraulic cylinder, as it is powered by a pump pushing the uncrushed neem page to dehulled seeds in a perforated cage or piston plate assembly at relatively high constant pressures, usually exceeding 50–100 MPa. This stress causes rupture of cells that contain oil and propel the released oil into tiny perforations into a collection tray, as expressed in and. The batch-based aspect of the process is suitable to its small-to-medium operations, with 10–50 kg per cycle and a 5–15 min dwell-time. At these circumstances, 30–40% yields are obtained, which are better than those of the manual techniques owing to hard, fibrous shells and thick oil of neem, as reported in and. Pre-treatment methods such as 8–10% drying over the sun or roasting at 60–80 °C lower viscosity, more effectively fracture the kernel, and improve recovery by 10–20%. At the same time, these treatments reduce residual oil in the cake to 4–8%, in line with the values offered[20].

Conversely, screw presses require a constantly rotating helical screw in the inside of a tapered, perforated barrel to cause progressive axial compression, and as such, it results in making them usable in high-throughput operations. As the seeds grow, the pitch reduces compression, boosting the oil displaced by the gravity separation; the capacities are used in amounts of up to 500 kg h^{-1}, as per. Both hydraulic and screw methods use constant pressure that is enough to break the hard low-bulk-density of neem seeds, hence preserving bioactive like azadirachtin, among others, solvent-free. Compared to screw presses, hydraulic systems are relatively simple and therefore less energy is required to run intermittently, since screw presses must be run continuously and must have cooling jackets to eliminate the effect of friction heating. Crude oil is clarified with mounted filters, which enable scalable sustainable production[18]. The average hydraulic press efficiency ranges at about 21 n.p.; contemporary expellers run of up to 45 n.p. when designed correctly. There are usually hardened alloy steels in his construction materials, particularly in critical compression parts, and it is resistant to abrasive wear by neem seeds, and assures of long life and also uniform performance.

D. Motorized and Automated Extraction Machines

Higher automation requires the use of electric motors, programmable logic controllers (PLCs), and sensors to optimize the extraction of neem seed oil by dramatically increasing the throughput to 100–1000 kg h^{-1} and minimizing labour by more than 90%. Screw presses or hydraulic rams that typically have a frequency drive rated 5–50 kW can be powered by electric motors that provide a torque with high accuracy to counter neem abrasive shells by using hardened alloy gearboxes. Automation simplifies workflow: hopper feeders, fitted with an ultrasonic level sensor, control feed rate; real-time PLCs monitor pressure (20–50 MPa), temperature (60–80 °C) through water jackets, and moisture (8–12%) and is dynamically adjusted, delivering 35–45%, which basic expellers are incapable[21].

Seeds are conditioned by integrated pre-treaters, such as sun-dryers, roasters, and dehullers; indigenous bio actives such as azadirachtin are not lost in solvents. Crude oil is separated at 25–40 wt % range by post-pressing centrifuges, vibratory screens, and filtration units. These systems have an energy efficiency of 15–30 kWh t^{-1} but can achieve 15–30 kWh t^{-1} with feedback loops that use NIR spectroscopy or vision systems to monitor fines and clogs. Rural cooperatives are served by small-scale units, ranging between USD 5,000 and 20,000, and the auto clean features are added in transition to industrial lines. These systems are beneficial, as their benefits include uniformity, less labour, and sustainability through the use of solar hybrids[22]. There are still difficulties, such as dust-covered sensors and reliance on grid power, which lead to hybrid architecture. Finally, this technology will facilitate a cross between the artisanal and commercial production, which will unlock the pesticidal nature of neem. Figure 3 shows the Classification of neem seed extraction technologies based on operating principle

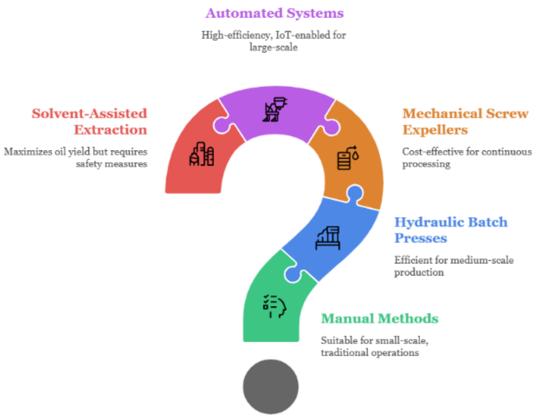

Fig.3. Classification of neem seed extraction technologies

IV. DESIGN AND WORKING PRINCIPLES

In this section, we will explore the specifics of engineering that the neem seed extraction machines are built on, why they are designed to operate in the way they do, and why some delicate choices made during their design to the specifications make it the best in the market.

A. Major Components

To extract the neem seed, the equipment has been designed based on the physical characteristics of the crop; high hardness, low bulk density, and viscous oil. In mitigating bridging risks, a hopper, and typically fitted with either vibratory or ultrasonic feeders, offers a continuous feed stream[22]. The core of the equipment is the pressing mechanism: in expeller systems, it is a constantly rotating helical screw in a tapered barrel that exerts progressive compressive force at 20–100 rpm, and in batch systems it is a hydraulic cylinder that can exert 50–100 MPa of statical pressure. The seeds are held in a cage or perforated barrel through which the oil is squeezed out of pre-drilled slits into collection trays, and the press cake is retained[23].

Power is supplied by electric motors which are 5–50 kW, and they are regulated with variable frequency drives and connected to hardened alloy-steel gearboxes with Rockwell hardness over 50 HRC in order to amplify the torque and withstand abrasion. Other assistive devices are preheaters or roasters in the range of 60–80 °C; this lowers the oil viscosity by 20–30 °C; centrifuges or vibratory screens after extraction; filtration units to retain bio actives like azadirachtin; PLCs; NIR sensors; and auto-feeders that maximize yields up to 35–45% with the high-end models.

B. Operating Principles

All these create the feasibility of mechanical pressing of neem seeds, thus the extraction of oil by preparation of the seed, crushing, and separation of the oil and press cake. It starts with hopper conditioning, during which vibratory or ultrasonic feeders ensured constant flow by opposing the low bulk density and very high hardness of the seeds and prevented bridging. Sun drying to 8–10% moisture level or roasting at 60–80 °C crack open the kernels, cut down the viscosity by 20–30%, and boosts the cell rupture, which increases the yield by 10–20%[14], [22].

The main part of the operation is the pressing mechanism that depends on the type of the system. In screw presses, a helical screw, constantly rotating inside of a tapered and perforated barrel, exerts a progressive axial force upon the seeds on the advancing side of the reducing pitch. This causes the rupture of oil cells, and this causes the oil to move sideways due to gravity through the fine slits by discharge gas into collection trays, and the fibrous cake is forced out of the outlet. Hydraulic presses are appropriate to batch (10–50 kg $cycle^{-1}$) and utilizes a cylinder powered by a pump to provide 50–100 MPa static pressures on de-hulled seeds that are restrained in a perforated cage or piston assembly in 5–15 min[19]. The hard shell and the viscosity of oil, which hampers the shell crushing, is overcome by uniform compression, and yields of 30–45% are attained, significantly better than by hand methods.
To reduce the viscosity without reducing bio actives like azadirachtin, heating units, electric roasters, or

steam jackets are often used in optimization. Crude oil is refined (organized by eliminating fines and moisture) through integrated filtration units (centrifuges or vibratory screens). Dynamic control of parameters—pressure to rupture the cell, temperature not exceeding an optimum of 64 °C based on Box–Behnken models of fluidity, and time, which is about 13–30 min at peak—to maximum recovery near 90% efficiency can be achieved using real-time monitoring with PLCs, NIR spectroscopy, or a sensor. The 5–50 kW variable frequency drives on 5–50 kW motors maintain a torque certainty in relation to abrasiveness with an objective of 15–30 kWh t^{-1} energy utilization. After the pressing, the separation of oil based on density is done in settling tanks or through centrifuges, and the remaining cake can be used as animal feed or biogas, which makes the technology a cycle. Throughput rates of 100–1,000 kg h^{-1} automated systems include feedback loops to avoid clogging by high-silica husks, and the others provide a rate of 100–1,000 kg h^{-1}[18]. The multi-faceted system design, including wear-resistant materials (hardened alloy steels with Rockwell hardness of more than 50 HRC and nitriding with the service life of 5,000–10,000 h), care over the operational parameters, including pressure and temperature, and proper engineering to operate continuously without using a lot of energy, are all present. The safety measures, such as emergency stops and dust removal, reduce the risks of explosion caused by the presence of the particulate itself. The combination of these factors enables scalable and chemical-free extraction methods that do not affect the pesticidal properties of neem oil to be used as a biopesticide and in other ways.

C. Design Considerations and Constraints

When it comes to the topic of neem seed extraction, the machine will be designed with the ultimate goal of ensuring maximum performance by means of a reasonable material choice. Hardened alloy steels (e.g., AISI 4140 or EN 24) or stainless counterparts are normally used to make components that are in high pressure and friction (e.g., screws, barrels, pistons, and cages). These alloys, with Rockwell hardness levels greater than 50 HRC, greatly decrease abrasive wear that radium as the hard shells and fibrous surfaces of the neem seed and therefore greatly enhance operational life of up to 5,000–10,000 h with continuous use. These parts are further strengthened by use of complementary surface treatments such as nitriding and chrome plating, which counter the silica-rich humus which coats the seeds[24].

The engineering plan has to balance the accuracy of control of the working variables. In the case of hydraulic systems, the maintenance of the pressures of statics ranging between 50–100 MPa are being entrusted to ensure residence time of 5–15 min. Simultaneously, the screw presses attain progressive compression by the means of a tapered barrel with the pitch decreasing 100 mm to 20 mm; the rotational speed used is 20–100 rpm. Thermal conditioning, either through steam jackets or the use of infrared heaters, is used to reduce seed oil viscosity by 20–30%, thereby extracting the product but not affecting azadirachtin structure. However, their limitation is associated with the sample size of neem with low bulk density, and the viscosity of the oil is high, which necessitates pre-treatment processes like roasting[25].

The suggested ambition of 15–30 kWh t^{-1} is followed regarding energy efficiency, supported by variable-frequency drives and PLC-based feedback loops that keep torque and moisture under observation with the help of NIR sensors. Scalability implies that the modular design is preferred, which can be expanded to rural and industrial scale; production rate can be between 10 and 50 kg $cycle^{-1}$ and scaled to much more than 500 kg h^{-1}. The priority is on safety measures since there is the chance of fine particulate ignition; in this regard, the architectures involve emergency stop systems and dust collection systems that limit the risks of explosions. Lastly, financial feasibility is pegged on local and low-cost manufacture that, subjected to their outputs, can yield handsome returns on investments at 35–45% yields[26], [27].

V. PERFORMANCE PARAMETERS

Neem seed extraction machines can be evaluated using several priority performance parameters that are all quantitative in the effectiveness of the extraction machine in terms of its operational viability and impact on economy. Most prominently is the quantity of oil extracted, which is taken as the weight of extracted oil per unit of mass of the neem seeds and, in the ways, optical systems are up to 35–45% or up to 44% under ideal conditions such as 64 °C temperature and fine particle size neem seeds. The efficiency of extraction ratio of the extracted oil to the total oil content in seeds depends on the pre-treatments, pressure, temperature, and period; it can almost go up to 90% beneath the heating of low viscosity. Sustainability prevents and costs are balanced by consuming energy of 15–30 kWh t^{-1} through efficient drives and sensors. A maximum throughput capacity of 100–1000 kg h^{-1} in automated units allows rural throughput to industrial scale. Lastly, wear and tear on hardened steels and sensor dirt-out all require frequent maintenance on 5,000–10,000 h life cycles to maintain uniform performance of the devices despite the agrast of neem.

A. Oil Yield

Oil yield means the weight of oil which is recovered per kg of neem seeds, which are directly proportional to the extraction efficiency of neem seed machineries. The maximum yields of optimized mechanical systems under optimum conditions of high temperature of 64 °C, small particle size of 0.212 mm, and a longer extraction time of approximately 133 min are 35–45% and 44%, respectively. These are far higher than the figures achieved under manual techniques at less than 30%, and may offer the economic impetus through ROI with high-valued biopesticide oil with the rural cooperatives[19].

Some of the influencing factors include: pre-treatments to soften hard, fibrous seedlings, minimising bridging in hoppers, temperature control to cut viscosity 20–30% without degrading azadirachtin; and pressure, 50–100 MPa hydraulic or progressive screw at 20–100 rpm[14], [19]. The decrease in particle size and moisture watched by NIR improves liberation through kernels among husks with silica. Scalability of a 100–1000 kg h^{-1} throughput allows balancing scalability of 15–30 kWh t^{-1} energy-efficient feedbacks to 100–1000 kg h^{-1}.

B. Extraction Efficiency

Efficiency of extraction, here expressed as the mass of extracted oil as divided by the total available oil content of neem seeds, typically 35–45% w/w, is a highly desirable measure of viability against mechanical extraction, typically being 85–90% when optimum conditions are achieved. This also overtakes the manual processes and ways of getting the majority of the yields of the solvent extraction untouched with chemical residues, while ensuring the biopesticide integrity of azadirachtin.

The major variables influencing are pre-treatments, including roasting or grinding, to disobey silica-laden husks and fibrous matrices, which contribute to activating oil release and inhibit hopper bridging. Access is maximized by optimum particle sizes via hammer milling, e.g., crystallizing into 0.2–0.5 mm, which Box–Behnken designs proved. Applied pressure, usually 50–100 MPa in hydraulic press or progressive in screw expeller, causes cell wall ruptures and dwell times of 5–15 min, so that recoveries can be maximized near 90%[15].

Heightened temperature brings about viscosity reduction in oil by about 20–30%, and this ensures the flow without heat removal of the heat-sensitive limonoids like azadirachtin. Long times (as long as 133 min of laboratory-optimized solvent–mechanical hybrids) are positively correlated with recovery, but extra-industrial screw presses can be efficient at continuous 20–100 rpm.

Intelligent systems employing NIR sensors and PLC feedback processes make online control of the moisture and pressure, thereby holding 85–90% efficiency at 15–30 kWh t^{-1}, as well as upscaling throughputs to 100–1000 kg h^{-1} . The problematic materials for use include hardened steels as high as 50 HRC; nevertheless, modular designs can guarantee high durability. Finally, economic ROI based on high efficiency of rural-to-industrial application is in place, diminishing waste and environmental impact.

C. Energy Consumption

One of the most important performance parameters used in the consideration of the economic feasibility, scalability, and footprint of any mechanical neem oil extraction machine is energy consumption. Real-time torque monitoring, moisture monitoring, and pressure monitoring by near-infrared sensors, together with integrated variable-frequency drives, programmable logic controllers, and optimization of systems, allow minimization of energy wastes at high yields[28].

The main factors are machine design: hydraulic presses have higher peak power but can work intermittently during rural use, while screw expellers can be progressively compressed at 20–100 rpm with lower average power consumption using tapered barrels. Pre-treatments such as roasting or fine grinding reduce oil viscosity by 20–30%, reducing by more than 50% the energy required to pump oil without decomposition of azadirachtin. Hopper vibrators eliminate bridging of low-density seeds and eliminate overload spikes.

Temperature control is very important; not more than 64 °C allows maximum flow but needs very fine heating controls to avoid overheating. NIR–PLC systems provide feedback loops which adjust parameters towards sub-20 kWh t^{-1} scales in modular systems between 100–1000 kg h^{-1} throughput. Abrasive silica husks raise wear, which raises energy consumption indirectly through inefficiencies, countered by hardened steels and nitriding.

Mechanical pressing avoids 30–50% of the energy used in solvent processes such as Soxhlet extraction with hexane evaporation and leaves no residues. This provides a greener extraction route. Rural electrification still presents problems that can be remedied with solar–VFD hybrids. ROI at low-energy levels with 35–45% yields underline sustainable production of biopesticides.

D. Throughput Capacity

Throughput capacity, the number of kilograms of seeds processed per hour, is a key performance indicator for the assessment of neem seed extraction equipment, particularly in terms of scalability and industrial feasibility. Rates of 100–1000 kg h^{-1} can be attained in optimized automated systems, allowing smooth scaling between rural small-scale processes, such as depulpers at 75–150 kg h^{-1}, and industrial scales that significantly exceed conventional processes, which normally achieve throughputs of the order of 10 kg h^{-1}.

Hydraulic presses are most effective in intermittent, low-volume rural work through batch-cycle operation, whereas continuous screw expellers can be scaled to 500–1000 kg h^{-1} with minimal downtime. Pre-treatments including depulping, roasting, and fine grinding alleviate bridging in fibre-based, silica-laden seeds, maintaining steady flow free of overloads[28]. Hopper vibrators and automated feeders further increase capacity by 20–30%.

Sensors such as NIR spectrometers for moisture measurement and PLCs for torque and pressure provide real-time adjustments to coordinate throughput with efficiency and energy use. Box–Behnken optimized conditions support high processing rates without reduction in yield. Hardened components serve abrasive husks with lifespans of 5,000–10,000 h, ensuring reliability at scale.

Mechanical systems have a more sustainable environmental profile due to continuous operation, while solvent extraction remains batch-limited and residue-forming. Rural hybrid systems using solar energy improve feasibility, and IoT integration expands scaling to cooperatives. Return on investment is supported by high throughput enabling daily tonnage sufficient for biopesticide markets, despite remaining electrification gaps.

E. Maintenance and Operational Problems.

The operational and maintenance issues are important factors of the stability, dependability, and profitability of mechanical seeking oil of neem machines, this being mainly due to neem seeds being defined with abrasive silica batteries and fibrous lamellar. Hoppers, screws, and barrels are routinely cleaned to avoid clogging and bridging; worn-out parts of the process, including expeller screws and cages, are also regularly replaced to maintain high operational efficiency[19]. The life of 5,000–10,000 h services may be achieved with the implementation of hardened steels and nitriding processes.

The main problem in operation is hopper bridging in low-density seeds, which can be overcome with vibrators and fine-grinding pre-treatments, as well as the abrasive wear that is accelerated by high pressures of 50–100 MPa, which results in downtime and indirect energy costs[8]. Prolonged runs lead to overheating and would require installation of temperature sensors and cooling devices to protect the heat-sensitive azadirachtin. Automation through PLC/NIR feedback loops is constructive to minimise the error go-round; although, a number of rural systems still exhibit electrification gaps.

Mechanical systems also require more regular maintenance compared to solvent extraction, but unlike solvent systems, they avoid the formation of residue, a characteristic of green practices. The appropriate observance of the procedures, like cleaning every day and inspection every quarter, guarantees the payback if failures are minimised and scalable production of biopesticides can be supported[29]. The figure 4 summarizes the key performance metrics governing mechanical neem seed oil extraction.

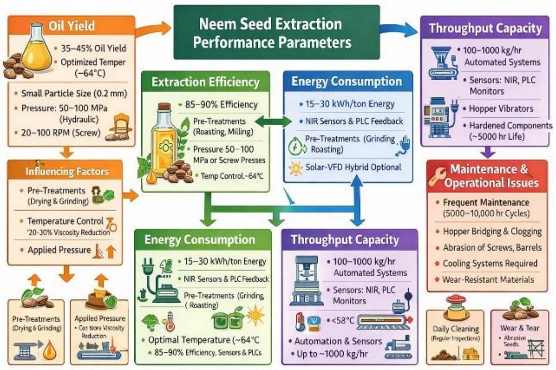

Fig.4. Key Performance Parameters of Neem Seed Oil Extraction

VI. COMPARATIVE ANALYSIS OF EXISTING SYSTEMS

This section is a systematic literature review of the literature that relates to mechanical neem oil extraction technologies and compares the working models of the hydraulic presses with the screw expellers. It further details their critical performance parameters of oil yield and energy consumption, throughput, and maintenance needs, by projecting lifespan of 5,000–10,000 h, and assesses their applicability along a scale of rural intermittent to industrial continuous processing. As compared to the higher-yielding solvent-based processes, the discussion points out that the residuals and environmental risk related to the solvent extraction can be reduced to the optimization of mechanical designs, Box–Behnken modelling, and pre-treatments, hence in accordance with the objectives of the findings biopesticide production.

Comparison of Different Various Machine Designs Reported in Literature

The literature singles out a range of both crude manual press systems and sophisticated press systems, which are continuous screw expeller systems, for extracting neem seed oil. Such systems are variably variable with respect to the scale of operation, efficiency in yields, energy requirements, as well as maintenance profiles. These four main design types are constantly listed as manual hand presses, hydraulic batch presses, continuous screw expellers, and a new variant of automated hybrid that includes sensor integration. The following provide comparative evaluation of these configurations, based on empirical research that describes the manipulation of naturally abrasive and fibrous neem seeds[16].

A subsistence farming sector is dominated by manual presses, most of which depend on levers and do not require any form of electricity. Their performance is, however, impaired by inconsistent pressure application that gets about 25% oil and high labour intensity. The reduction of yield is also introduced at an even greater rate in the absence of pretreatments like roasting, which can increase throughput up to 20–30%[19].

The range of pressure discharged by hydraulic presses is 200–500 bar, employed in batch mode, hence supporting rural intermittent operation; common cycles are considered to have 100 kg load and 35–40% oil yield at an optimal temperature of 64 °C, acquired in the Box–Behnken predictions. Peak power requirements may be 50 kW, and the silica husk tends to clog, often leading to the need to have solid hydraulic systems together with vibratory hoppers[18].

Screw expellers work on a continuous basis and take advantage of tapered barrels rotating at 20–100 rpm to produce yields of 40–45%. Their efficient compression system ensures that energy use is less than 20 kWh t^{-1} for industrial throughput of more than 500 kg h^{-1} . By nitriding the screw components, wear caused by abrasive husks can be reduced and the operation life increased to some 10,000 h[30].

New hybrid systems combine near-infrared (NIR) and programmable logic controller (PLC) sensors to optimise the real-time torque and moisture to achieve yields of 48% and process 0.212 mm seed biomass in 133 min at 64 °C. These systems are also able to save as much as 20–30% of energy as compared to traditional presses. Integrating solar drives with variable-frequency drives (VFDs) solves the issue of intermittency of power supply in rural settings.

Grinding or depulping is a commonly seen pre-treatment technique in all designs that is effective in averting bridging phenomena and boosting productive capability by 20–30%. Even though oil production is usually lower (45–50%) with the use of mechanical systems than with the use of solvents, they offer longer-term sustainability since no layer of chemical residues is left behind. Depending on scale, extraction is best selected such that manual and hydraulic presses are most economical in less than 200 kg h^{-1} rural operations, while screw and hybrid systems offer commercially viable performance with return on investment thresholds of 35–45% yields[20].

This comparative study highlighted in the Table 2 shows how extraction technology has been made more media-of-measurement oriented and how designers have tried to balance some of the challenges that are inherent with the fibrous and abrasive nature of neem with scalable and environmentally benign extraction approaches.

Table 2. Comparative Assessment of Mechanical Neem Seed Oil Extraction Methods

Design Type	Oil Yield (%)	Energy Use (kWh/ton)	Throughput (kg/h)	Maintenance Needs	Suitability
Manual Hand Presses	20–30	<5 (manual labour)	<10	Minimal; hand-cleaning	Rural, intermittent; low capital
Hydraulic Batch Presses	35–40	15–25 (peak high)	50–200 (batch)	Moderate; seal/filter replacement every 1,000 h	Small-scale rural, simple ops
Continuous Screw Expellers	40–45	10–20 (avg. low)	100–1,000	High; screw/cage wear (5,000–10,000 h with hardening)	Industrial; scalable
Automated Hybrids (PLC/NIR)	42–48 (optimized)	<15 (feedback loops)	200–1,000	Low-moderate; remote monitoring	Cooperatives modular

VII. APPLICATIONS AND INDUSTRIAL RELEVANCE

The multiple uses of neem oil and the neem-related by-products make the neem seed extraction equipment a catalysing investment within a range of applications that span between the empowerment of smallholder farmers and large-scale industrial production processes.

A. Small-Scale Farmers and Rural Enterprises

To these stakeholders, the miniature and low-cost neem seed extraction machines are a key intervention of value addition, where local processing and direct market access of produce by these stakeholders will be possible. During intermittent rural work, it is appropriate to use manual hand presses and primitive hydraulic systems with oil yields of 20–40%, with little energy input and without the need to electrify the system, for on-farm biopesticide and cosmetic manufacturing[2].

Designs with fewer impositions of drudgery as compared to manual depletion, pre-treatment systems including roasting, boost the flow of oil by 20–30%, and maintenance of premium markets with azadirachtin concentrations and no solvent residues are all solar-powered variations of the design. The natural biodegradability of neem oil fits perfectly in environmentally friendly pest-control paradigms, once again allowing smallholders to be accorded economic and environmental power welling at the same time. The scaling up of cooperatives to compound rural operations is facilitated by microfinance projects and specially designed training[31].

B. Commercial Neem Oil Production

Massive extraction equipment such as continuous screw expellers and automatic hybridized systems holds such importance in industrial manufacturing of high-grade neem oil, thus serving the needs of diversified sectoral demand. The neem oil holds a wide range of technology usage, including clinically viable pharmaceutical preparations, antimicrobial agents, biodiesel precursors, cosmetics, and biopesticides.

Optimization of some of these processes maintains the bioactive component azadirachtin, which facilitates inventions of sustainable fuels and environmentally friendly agrochemicals. Such applications are economically viable, having yields in the range of 45%, and supplying global markets with a minimal number of residues compared to solvent-based methods[32].

C. Environmental and Economic Benefits

The non-toxicity and biodegradability of neem oil offer a viable substitute for synthetic pesticides, which subsequently effects an essential contribution to sustainable agricultural growth and reduction of ecological footprints. Locally, neem seeds are processed and locally produced, leading to rural progress, job creation, and increased income of farmers, particularly in areas where neem grows in large quantities.

The use of neem seed cake as a by-product of oil extraction and neem-based industries, by using the product as an organic fertilizer or as animal feed, further positively benefits the economy and increases the circularity of neem-based industries[33]. This level of holistic use comes in line with the knowledge of a circular economy because it cuts down waste and increases resource efficiency in agricultural and industrial value chains. The neem oil philosophy of multifunction provides therapeutic benefits as well as suitable use in agriculture, and therefore finding more efficient ways to extract it maximizes the benefits of the product. In that regard, incessant invention of neem seed extraction equipment will drive growth in all its uses and support sustainable development efforts on a global scale.

VIII. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although neem oil has these favourable properties, it suffers from a major setback of being photodegraded, thus causing the loss of its antifeedant and insect growth-suppressing properties. Its active components are, therefore, inherently unstable and require the use of advanced encapsulation and formulation technologies to preserve the bioactivity of the oil during storage and use. The separation of certain bioactive compounds in neem oil, in particular azadirachtin, is complicated further by the complex molecular structure and low concentration of the same in the seed and thus requires careful separation processes, which are often energy-intensive[3], [34].

The scope of neem oil application is quite wide; however, the process of extracting this important oil is nevertheless associated with salient challenges, first of all, how best to exploit the product to extract the oil maximally at minimal cost and environmental impact. To fulfil this goal, it is necessary to design machinery that is energy efficient and able to recover high-quality oil with a maintained profile of active constituents. On the technological side, the advances that should be made are to increase the mechanical separation efficiency of thin oil fibrous seed matter, as well as coming up with equipment that can be subjected to the abrasiveness of neem seeds[23].

The high costs of the initial capital investment in sophisticated technologies are also considered a challenge to small-scale farmers and small entrepreneurial corporations; therefore, the challenge is a desperate necessity to use cost-effective designing solutions and affordable financing options. The aim of seeking sustainable, inexpensive technologies that can combine these features is still necessary; further studies on the same are thus urgently needed[35].

The implementation of artificial intelligence and machine learning into extraction parameters may also help to optimize the operational parameters by forecasting the best conditions, depending on the properties of the seeds and the required oil purity. These systems enable real-time optimization of the working parameters, thus increasing yield and reducing production of wastes. Furthermore, neem oil farm-to-consumer transparent traceability, and the authenticity and quality of products, can be provided under the influence of blockchain technology applications.

Other modalities of extraction that may be investigated in the future include microwave-assisted extraction methods or ultrasound-assisted extraction methods, as discussed in other applications of the same oilseeds where they have been shown to enhance the yield and reduce the amount of solvent used. These new strategies may also take the innovation of neem oil production profiles to the next level by reducing energy usage and, hence, affecting the environment[23], [35]. The mechanism of membrane-assisted downstream fractionation and purification of the extracted oil may be beneficial, using the incorporation of deep eutectic solvents and ionic liquids as alternatives to standard organic solvents, which may appear green.

However, light sensitivity of neem oil is also a glaring weakness; exposure to light causes the biodegradation of neem oil and the loss of its antifeedant and insect growth inhibitory properties .This biological instability highlights the importance of sophisticated techniques of encapsulation and formulation strategies that are used to maintain the bioactivity of the oil during storage and usage .Also, the enhanced isolation of certain bioactive ingredients, e.g., azadirachtin, is othered by the compound's complex molecular structure and low concentration in seeds, which requires accurate and usually energy-demanding separation techniques.

IX. CONCLUSION

This review has presented a comprehensive examination of the range of technologies available for neem seed oil extraction, spanning from primitive manual methods to sophisticated computerized systems designed to enhance efficiency and scalability. Fundamentally, these technologies remain grounded in the long-established principle of mechanical pressing—a technique that, despite being over a century old, continues to evolve through innovations in seed pre-conditioning, hydraulic and screw-driven mechanisms, and post-extraction filtration. Engineering decisions such as the incorporation of wear-resistant alloys in high-pressure components, thermal control to reduce oil viscosity, and optimized compression geometries are documented to exert a direct influence on key performance indicators, including oil yield (typically 25–40 wt.% of seed), extraction efficiency (approaching 90 wt.% of available oil), throughput (approximately 5 $kg \cdot h^{-1}$ for village-scale units and exceeding 500 $kg \cdot h^{-1}$ for industrial systems), and overall energy consumption[16], [36].

Comparative analysis indicates that hydraulic presses are well suited for smallholder contexts due to their relatively low capital cost, operational simplicity, and adaptability to intermittent rural use, whereas continuous screw expellers and solvent-aided systems offer greater commercial profitability but face challenges associated with higher investment costs, solvent residues, and environmental burdens. Neem oil continues to play a pivotal role across multiple applications, including empowering on-farm value addition, advancing biopesticide adoption as an environmentally benign alternative to synthetic agrochemicals, and enabling patentable innovations in pharmaceuticals and biofuels[29]. Nevertheless, persistent challenges remain, notably the photodegradation of azadirachtin, the need for economically scalable low-cost technologies, and underexplored opportunities for automation and intelligent process control.

The novelty of this synthesis lies in proposing a hybrid paradigm that integrates low-cost mechanical presses with solar-assisted and ultrasonic enhancement mechanisms, supported by Internet-of-Things (IoT) sensors for real-time process optimization. Such integrated systems have the potential to improve small-farm extraction efficiency by 20–30% while simultaneously reducing energy requirements, operational waste, and reliance on solvent-based methods[2]. These innovations offer a pragmatic bridge between rural operational realities and industrial performance expectations, reaffirming the relevance of neem within sustainable agro-economic frameworks.

Future research should prioritize field-scale validation of these integrated systems, alongside the selective breeding and deployment of high-oil-yield neem cultivars to maximize extraction potential. Ultimately, the advancement of neem seed oil extraction technologies transcends mechanical engineering alone, representing a broader step toward sustainable, resource-efficient, and environmentally responsible development across the Global South.[29]

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