Beyond Medicine: Nutraceutical Approaches for Comprehensive Management of Polycystic Ovarian Syndrome

Apurva S. Patil, Sujan R. Mulani, Mehvish L. Mushrif, Chandraprabhu Jangme, Snehal P. Bongarde

Department of Pharmacology, D. Y. Patil Education Society, D. Y. Patil College of Pharmacy, Kadamwadi, Kolhapur, 416003, Maharashtra

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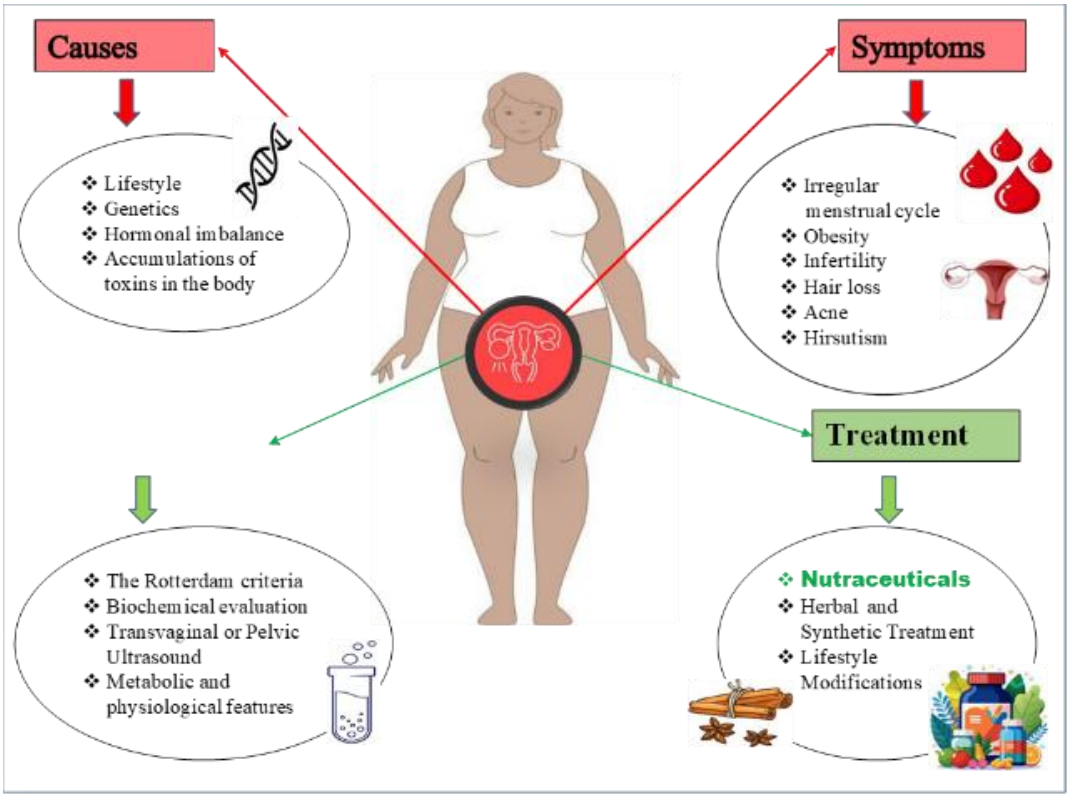
ABSTRACT

Polycystic Ovary Syndrome (PCOS) is a common endocrine and metabolic disorder characterized by ovulatory dysfunction, hyperandrogenism, and polycystic ovarian morphology. Insulin resistance, adipose tissue dysfunction, oxidative stress, chronic low-grade inflammation, mitochondrial impairment, and altered insulin-signaling pathways are all part of the multifactorial etiology of PCOS, which leads to hyperandrogenism and metabolic disorders. This review emphasizes how dietary changes, vitamins and minerals, nutraceuticals, antioxidants, herbal extracts, and traditional pharmaceutical treatments might help manage PCOS. Investigation indicates that dietary and lifestyle changes can considerably lower obesity, increase insulin sensitivity, and restore ovulatory function. Nutraceuticals have shown positive impacts on metabolic and reproductive outcomes, making them interesting adjuncts in the management of PCOS. Herbal remedies like curcumin, berberine, and cinnamon have demonstrated promising effect in enhancing metabolic health and hormonal balance. Supplementing with necessary vitamins and minerals may also promote healing and general health. In order to improve health outcomes and the quality of life for women with PCOS, this review highlights the significance of including dietary recommendations and nutraceutical therapies into PCOS therapy.

Graphical Abstract



Beyond Medicine: Nutraceutical Approaches for Comprehensive Management of PCOS

Manuscript highlights:

- PCOS being a complex condition includes genetic predisposition, insulin resistance, inflammation, and hormonal imbalance which is a serious condition affecting women health.
- For early management, a precise diagnosis based on clinical, biochemical, and imaging criteria is necessary.
- A safer substitute or supplement to synthetic medications in PCOS treatment is offered by nutraceuticals.
- Minerals and vitamins and ayurveda approaches are important for enhancing ovarian health, insulin sensitivity, and metabolic function.

Nutraceutical strategies work in tandem with dietary and lifestyle changes to provide comprehensive PCOS management

Keywords: Women Health, Diagnosis, PCOS, Nutraceutical, Antioxidant, Vitamins, Lifestyle, Herbal Extracts

INTRODUCTION

Polycystic ovarian syndrome is a chronic endocrine condition that requires early diagnosis and ongoing treatment to enhance metabolic and reproductive health outcomes.

The first line of treatment for all women with PCOS, regardless of body weight, is lifestyle modification, which includes dietary adjustments and regular exercise. Regular testing for psychological comorbidities and cardiometabolic risk factors is also advised to lower long-term morbidity and enhance quality of life [1].

Hyperandrogenism, ovulatory dysfunction, and higher cardiometabolic risk are the hallmarks of PCOS, a complex endocrine-metabolic condition. A major pathophysiological trait that contributes to hyperinsulinemia, androgen excess, and metabolic problems is insulin resistance [2].

PCOS, a multifactorial and polygenic endocrine disorder that affects women of reproductive age worldwide, is often referred to as hyperandrogenic anovulation or Stein-Leventhal syndrome [3].

Follicle-stimulating hormone (FSH) and gonadotropin-releasing hormone (GnRH) are also linked to the underlying causes of PCOS, despite a hormonal imbalance that involves luteinizing hormone (LH) [4].

Numerous dermatological conditions, including acanthosis nigricans, acne, psoriasis, hidradenitis suppurativa, androgenetic alopecia, and hirsutism, have been linked to insulin resistance. The proper development of the epidermal structure depends on the natural balance between keratinocyte proliferation and differentiation, which insulin typically helps to maintain [5].

It is being shown that nutraceuticals, composed of bioactive food-derived compounds like inositol's, omega-3 fatty acids, and phytonutrients with antioxidant effects, could affect oxidative stress pathways associated with PCOS, lipid metabolism, and glucose homeostasis [6,7].

Vitamins (particularly D and E) and vital minerals (calcium, zinc, and selenium) also support endocrine and metabolic health and have been shown to improve insulin resistance, inflammation, and menstrual cyclicity when combined with lifestyle modification [6]

Pathophysiology

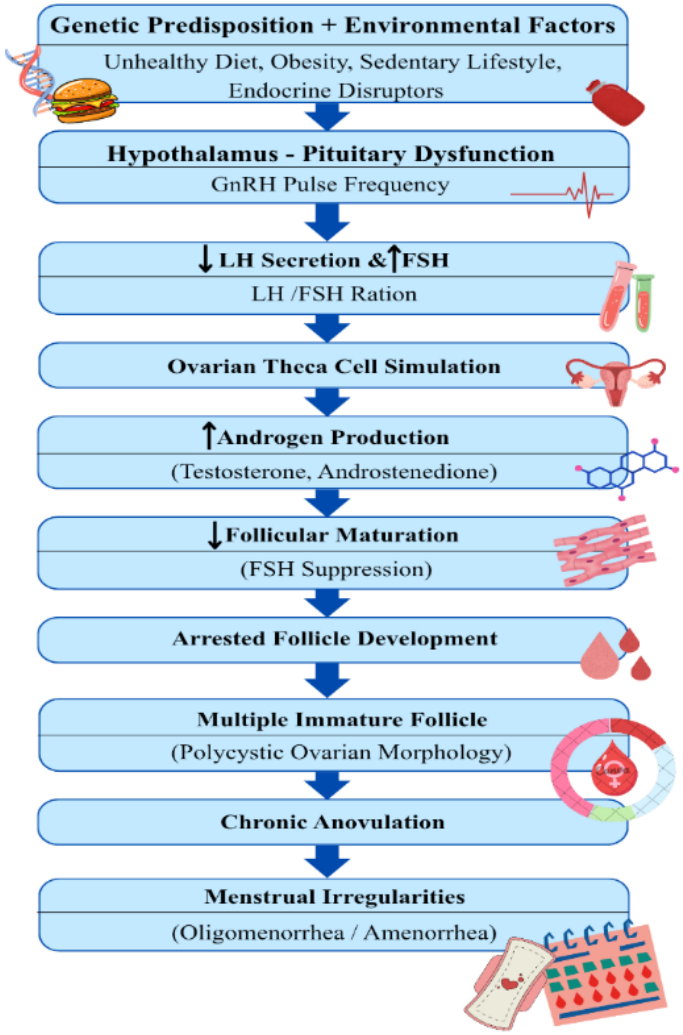


Fig. (1). The systemic pathophysiology of occurrence of PCOS.

The interplay between neuroendocrine levels, metabolic levels and ovarian anomalies may contribute to the development of polycystic ovarian syndrome [8]. Genetic predispositions and environmental factors such as unhealthy diets, obesity due to insulin resistance, sedentary lifestyle and endocrine disruptors leads to increase in the GnRH frequency associated with the hypothalamic and pituitary dysfunction. Increased GnRH levels lead increased levels of LH and decreased levels of FSH because of which the theca cell of ovaries get stimulated. Stimulated theca cells lead to increase androgen synthesis, decreased follicular maturation, follicular arrest and accumulation of multiple immature follicles leading to chronic anovulation, oligomenorrhea, amenorrhea, hormonal imbalance and infertility.

Etiological Background of PCOS:

Polycystic ovarian syndrome (PCOS) affects 5% to 10% of women of reproductive age [9,10]. The disease occurs at menarche and is characterized by oligomenorrhea, amenorrhea, anovulation, cystic ovaries, an increased LH/FSH ratio, obesity, hirsutism, and insulin resistance. Cystic ovaries produce significant amounts of androstenedione, testosterone, and 17αOH-progesterone. The cysts are fluid-filled fragments of atretic follicles that lack granulosa cells. As stated in the scientific literature in 1935 [11], the cause of PCOS is still unknown.

There are three main theories: PCOS results from an increased LH pulse frequency and amplitude caused by a fundamental neuroendocrine abnormality; The condition is brought on by a lack of insulin activity, which results in hyperinsulinemia; and variations in the FSH response are the main issue, which arises in the ovary [12].

Inositols (Myo-inositol or D-chiro-inositol, including inositols in individual or combination formulae) were examined in 86 different research as case studies of nutraceutical and herbal drugs. Anthropometric results (49.0%), metabolic outcomes (64.0%), and reproductive characteristics (95.3%) were the most often reported clinical features of PCOS in these investigations. Of these studies, negative results were observed in more than one-third (38.4%). Cinnamon was investigated in 14 cases. In these investigations, metabolic outcomes (85.7%), anthropometric outcomes (64.3%), and reproductive outcomes (57.1%) were the most commonly reported features of PCOS. Adverse results were reported in 57.1% of these studies [13].

Diagnosis

The Rotterdam criteria

After all other relevant conditions have been completely ruled out, polycystic ovarian syndrome is identified by ultrasonography, clinical or biochemical hyperandrogenism, and polycystic ovarian morphology. These norms recognize PCOS's range and enable the identification of many phenotypes with unique metabolic and reproductive risk profiles. Before confirming the diagnosis, conditions such hyperprolactinemia, thyroid illnesses, androgen-secreting tumors, and congenital adrenal hyperplasia must be checked out [14].

Biochemical evaluation

It involves detecting sex hormone-binding globulin when needed and assessing total or free testosterone levels to confirm hyperandrogenism. Ovulatory dysfunction is characterized by menstrual irregularities like oligomenorrhea or amenorrhea [15].

Transvaginal or pelvic ultrasound

Helps identify an increased number of follicles per ovary or increased ovarian volume. Current diagnostic guidelines highlight criteria based on age, discourage the use of ultrasound for diagnosing adolescents, and stress the importance of clinical judgment to guarantee timely and precise diagnosis of PCOS [15].

Metabolic and psychological features

Women with PCOS often have central obesity, insulin resistance, low glucose tolerance, dyslipidemia, and an increased risk of heart disease and type 2 diabetes. Furthermore, it has been repeatedly observed that stress, depression, body image issues, and a decreased quality of life are more prevalent, underscoring the necessity of comprehensive evaluation and care that goes beyond reproductive symptoms [16].

Intracellular Pathways Involved in PCOS

Sr no.	Pathways	Key Events	Major Actions	Physiological outcomes	REFERENCES
1.	PI3K \ Akt(PKB) Pathway	• Enhanced by phosphoinositide 3-Kinase (PI3K) pathway • Conversion of PIP2-PIP3 • Activation by PDK-1 and Mtroc-2	• Translocation of GLUT-4 to cell membrane • Activation of Glycogen synthase and endothelial nitric oxide synthase. • Phosphorylation of (FoxO1).	• Enhance glycogen synthesis in skeletal muscle, adipocytes and hepatocytes • Increase nitric oxide production in endothelial cells.	[17]
2.	MAPK Pathway	• Activation of extracellular	• Regulate the transcription factors	• Controls development,	[18]

		signal –regulated kinase (ERK) • Formation of endothelin-1 in endothelial cells.		division and proliferation	
3.	Insulin Resistance	• Reduce insulin signaling	• Reduce SHBG, or sex hormone-binding globulin. • Raise luteinizing hormone (LH) and follicle stimulating hormone (FSH)	• Increase in ovarian androgen synthesis and development of hyperandrogenism	[19]

Table 1. Intracellular pathways involved in PCOS with key events, major action and physiological outcomes.

Role of Vitamins and Minerals in PCOS

Vitamins

Vitamin D

Numerous studies are connecting vitamin D levels to various symptoms of PCOS, such as insulin resistance, infertility, and hirsutism. Vitamin D is thought to affect the onset of PCOS by modifying hormones and gene expression, subsequently impacting insulin metabolism and reproductive health [20]. While some studies indicate that vitamin D levels are similar in women with and without PCOS, other studies have revealed that vitamin D levels are both higher and lower in women with PCOS. According to studies, 25-hydroxy vitamin D (25OHD) levels in women with PCOS typically range from 11 to 31 ng/ml, with a significant portion (67–85%) having levels below 20 ng/ml [21]. Also, 10–60% of adults around the world have vitamin D deficiency, indicating the importance of vitamin D in maintaining systemic health and preventing serious diseases like cardiovascular disease, cancer, autoimmune disorders, and emotional issues like depression and chronic pain [22].

Vitamin A

In overweight women with PCOS, obesity and decreased glucose metabolism are linked to higher levels of retinol-binding protein 4 (RBP4). Vitamin A promotes the transcription of enzymes involved in follicular growth and differentiation through its active metabolite retinoic acid. Normal function of ovaries and folliculogenesis are maintained by adequate levels of vitamin A, however excess intake should be avoided as it can disrupt endocrine balance.

Vitamin B (B6, B12)

These vitamins help the body break down lipids, carbohydrates, and amino acids since they are coenzymes. This enhances the body's use of glucose and insulin. High levels of homocysteine, which are common in PCOS and are associated with decreased blood flow to the ovaries and infertility, are lowered by folate and vitamin B12.

Vitamin C

Ascorbic acid, sometimes referred to as vitamin C, is a micronutrient acid that the body only needs in trace amounts for normal tissue and cell formation. Because vitamin C is soluble in water and can be found in urine, it should be taken consistently. Vitamin C demonstrates antioxidant qualities by removing peroxyl radicals and regaining the antioxidant qualities of fat-soluble vitamin E. Overall, intracellular and cell membrane lipid peroxidation is beneficially prevented, much like the antioxidant action

Vitamin E

It reduces oxidative damage in ovarian tissue and reduces the lipid peroxidation of cell membranes. Vitamin E supports women with PCOS improve follicular integrity, improve menstrual regularity, and improve ovarian responsiveness by lowering oxidative stress and inflammation.

MINERALS

Magnesium

Magnesium is an important macro-mineral that the human body uses for over 300 metabolic processes, including blood pressure management, neurological-muscular communication, DNA and RNA synthesis, and the regulation of insulin, fatty acid, and protein metabolism.

It is the most significant cation inside cells. Bones contain about 60% of the body's magnesium, with the remainder being found in soft tissues and the extracellular space [23].

Zinc

More than 3000 proteins contain zinc, a crucial trace mineral that is involved in over 100 enzyme-mediated activities. Zinc is found in significant quantities within the cell. It has biological roles in developing cells and growth, enhancing immunity (anti-cancer immunity and wound healing), signal transduction regulation, insulin and glucose metabolism, enzyme cofactors (enzyme activation and inhibition), food metabolism, and DNA and RNA synthesis (DNA synthesis, modification, and replication).

A plasma concentration of less than 60 µg/dL is considered to be a zinc insufficiency. Zinc deficits may result from decreased intake (unhealthy meat consumption or vegetarianism/veganism), decreased absorption (more cellulose from plant-based foods and extra phytates from unleavened bread), higher losses, and increased demand (growth phases) [24].

Selenium

Selenium is an essential trace mineral that is necessary for many biological metabolic activities, such as the metabolism of lipids, carbohydrates, and other substances [25]. A randomised, double-blind, placebo-controlled study was conducted to determine the effects of selenium supplementation on asymmetric dimethylarginine (ADMA), cardiometabolic risk factors, and hormonal status in women with PCOS.

The study involved 66 women with PCOS, ages 18 to 45, who were randomly assigned to receive either 200 µg/d selenium or a placebo for 12 weeks. The findings demonstrated that there was no relationship between the lipid profile or hormone levels and the 12-week selenium treatment [26, 27].

Chromium

It has been found that chromium improves glucose tolerance by lowering insulin resistance [28]. In T2DM patients, chromium supplementation reduces blood sugar, lipids, anaemia, and plasma insulin levels in a dose-dependent manner [29].

Furthermore, chromium improves hepatic f3-cell and insulin sensitivity by increasing insulin binding to its receptors and stimulating insulin receptor production [30]. Nevertheless, there is not enough proof that chromium can improve the metabolic and clinical problems associated with PCOS. Although chromium supplementation causes oxidative stress, DNA damage, genomic instability, and carcinogenicity, care must be taken when mentioning it [31, 32].

Dietary Modification

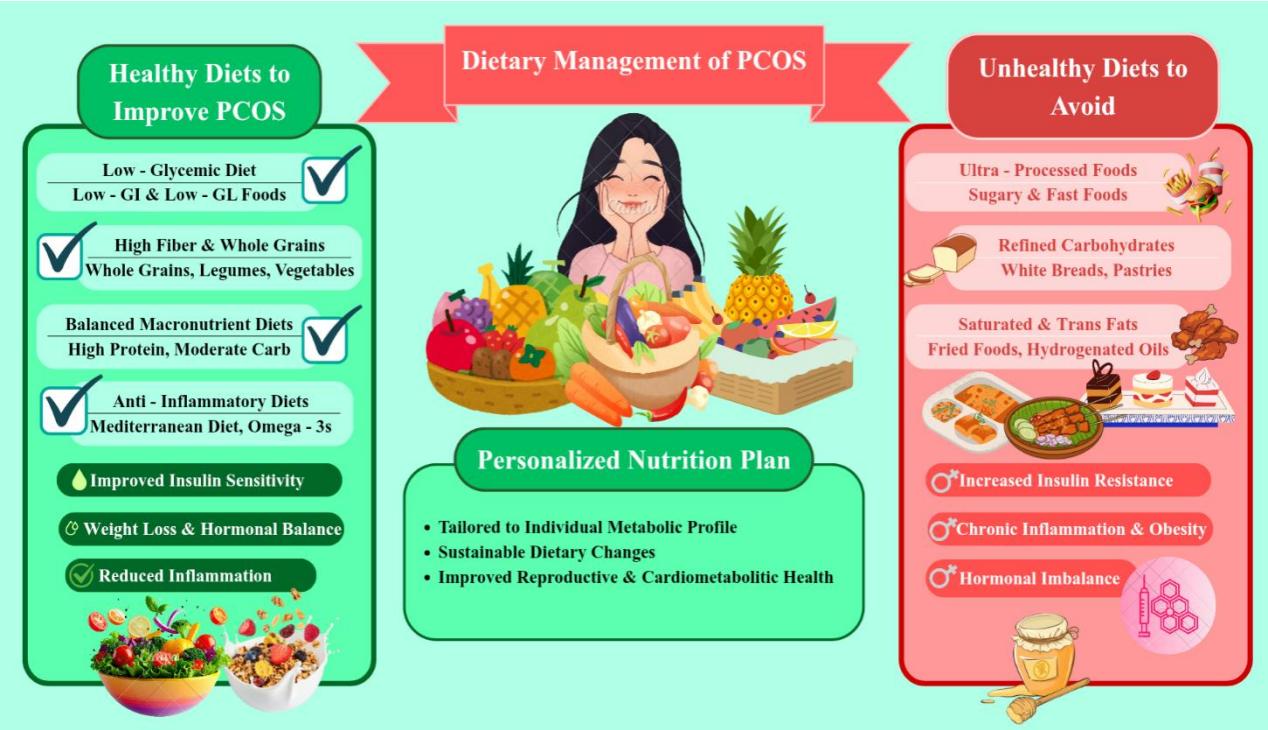


Fig. (2). Dietary managements in PCOS.

Dietary modification is crucial to the treatment of polycystic ovarian syndrome because it increases insulin resistance, hormonal imbalance, and metabolic dysfunction. Nutritional therapies targeting weight loss, glycemic control, and inflammation reduction were found to significantly improve reproductive and cardiometabolic outcomes. Even little dietary adjustments can enhance menstrual regularity and restore ovulatory function in overweight individuals with PCOS [33]. Women with PCOS are advised to follow low-glycemic index and low-glycemic load diets in order to reduce postprandial insulin spikes and enhance insulin sensitivity. Diets high in whole grains, legumes, vegetables, and fiber can help control blood sugar levels and reduce hyperandrogenism. Additionally, it has been demonstrated that women with PCOS can maintain good metabolic health and control their weight with balanced macronutrient diets high in protein [34]. Anti-inflammatory diets like the Mediterranean diet emphasize fruits, vegetables, whole grains, nuts, olive oil, and omega-3 fatty acids. These diets have been used to address key metabolic abnormalities in PCOS and have been linked to improvements in lipid profiles, increased sensitivity to insulin, and decreased systemic inflammation [35]. Dietary management of PCOS calls for avoiding ultra-processed foods, saturated fats, and refined carbohydrates. In excess of these foods worsens inflammatory pathways, obesity, and insulin resistance. It is strongly recommended that women with PCOS obtain personalized nutritional advice based on their distinctive metabolic profiles and cultural preferences so as to reap long-term, sustainable benefits [36].

Role of Antioxidants in PCOS

Lipid-soluble antioxidant, Vitamin E (α-tocopherol)

Vitamin E decreases lipid peroxidation and protects cell membranes from damage from oxidation. Clinical studies have demonstrated that vitamin E supplementation significantly lowers malondialdehyde levels and improves lipid profiles and insulin sensitivity in female PCOS patients. When combined with other antioxidants, vitamin E may enhance ovulatory activity and lessen inflammatory reactions [37].

Ascorbic acid (vitamin C)

Ascorbic acid neutralizes free radicals and aids in the regeneration of other antioxidants like vitamin E. Improvements in endothelial function, oxidative stress markers, and fasting glucose levels in PCOS have all

been associated with vitamin C. It works in tandem with vitamin E to improve total antioxidant capacity and hormonal balance [38].

Coenzyme Q10

Coenzyme Q10, referred to as ubiquinone, exhibits strong antioxidant properties and is vital for mitochondrial electron transport and cellular energy production. Coenzyme Q10 supplementation has been found to improve insulin resistance, lower oxidative stress, and effectively alter inflammatory and androgenic hormone phenotypes in women with PCOS, confirming its therapeutic potential in total PCOS management [39].

Alpha-lipoic acid (ALA)

By raising the uptake of glucose and mitochondrial activity and decreasing oxidative stress, alpha-lipoic acid (ALA), a strong endogenous antioxidant, increases insulin sensitivity. Supplemental intake of ALA has been observed to improve lipid profiles, lower inflammatory markers, and significantly decrease HOMA-IR in women with PCOS. Due to its double solubility in lipid and aqueous environments, it offers wide cellular antioxidant immunity, which makes it highly beneficial in metabolic conditions linked to PCOS [40].

N-acetylcysteine (NAC)

One of the body's most important intracellular antioxidants, glutathione, is created from N-acetylcysteine (NAC). By maintaining pH balance and suppressing hyperinsulinemia-induced generation of testosterone, NAC minimizes oxidative stress, improves insulin sensitivity, and improves ovulatory function. NAC intake, either individually or in combination with traditional medicines, was demonstrated in clinical trials to improve menstrual irregularity and fertility results in women with PCOS [41].

Nutracutical in PCOS Management

Since nutraceuticals may target insulin resistance, hyperandrogenism, oxidative stress, and inflammation, they are growing increasingly popular as adjuvant therapy for polycystic ovarian syndrome. These food-derived bioactive chemicals provide an additional strategy to medication and change in lifestyle. They have particular appeal for long-term usage in women with PCOS due to their good safety profile [42].

Oziva Plant based her balance for PCOS

Iincludes phytonutrients and adaptive herbs to promote liver cleansing, stress response, and hormone equilibrium. This can indirectly assist control cycles and lessen the imbalances in hormones associated with PCOS.

The Good bug balance Super Gut powder:

Aim is to promote the gut flora, which is becoming more and more important for controlling inflammation and metabolism in PCOS. Insulin susceptibility and general hormone equilibrium may be impacted by improved gut health.

Carbamide Forte PCOS balance gummies:

Inositol’s (myo- and/or D-chiro-inositol), vitamin D, chromium, N-acetylcysteine (NAC), etc., are frequently used to enhance ovulatory regulation, hormone modulation, and insulin responsiveness.

Pure nutrition PCOS Balance tablets:

Inositol isomers, vitamin D, zinc, and antioxidants are often used to improve metabolic health, hormonal balance, and inflammation reduction—all of which are crucial for managing PCOS symptoms.

Herbal Extracts in PCOS Management

S.No.	Drug/ Agent	Botanical name	Mechanism of action	Typical dosage	Effects	REFERENCES
1.	Chaste berry tree	Vitex angus-castus	May modulate pitutary hormones (decrease prolactine, increase FSH) balancing LH/FSH and supporting ovulation and cycle regularity.	About 20-40 mg of extract per day (usually in trials for cycle balance)	(often in research on cycle balance) strongest clinical evidence for cycle management among herbs; extensively researched for irregular menstruation.	[43,44]
2.	Black cohosh	Cimicifuga racemosa	Affects estrogen receptors, oerhaps reducing LH and promoting ovulation.	20-40 mg per day as a supplement (depending on the extract)	When combined with clomiphene, certain therapeutic benefits for ovulation induction have been seen.	[45]
3.	Cinnamon	Cinnamomum cassia/ C. verum	Enhances insulin sensitivity, lowers glucose and insulin during fasting, and may provide physiological assistance	333 mg extract -2-3 times per day	There is moderate clinical evidence for better glucose control; studies dosage vary; depending on tolerability, use ceylon or cassia.	[46,47]
4.	Tribulus	Tribulus terrestris	May maintain the balance of reproductive hormones and encourage ovulation and	85-250 mg of concentrated extract per day (conventional dosage)	Initial findings: brief research comparing ovulation rates with clomiphene.	[46]

			regular menstruation			
5.	Licorice root	Glycyrrhiza	Anti-androgenic action that might lower testosterone and maintain hormonal balance	200-400 milligrams of extract each day	Frequently made with other herbs; watch out for changes in potassium and blood pressure; unsuitable for prolonged high dosage.	[48]
6.	Peony	Paeonia lactiflora	In conventional combination: might support ovarian morphology and regulate hormone production	Used in formulations as opposed to its own (varies)	Typically, a component of multi-herb formulations; preclinical and animal evidence.	[49,50]
7.	Fennel	Foeniculum vulgare	Decrease LH abnormalities and increase FSH in certain preclinical data	1-2 grams of seeds or its equivalent each day; tea or extract	Preclinical and conventional data, which might aid in hormonal balancing.	[51]
8.	Shatavari	Asparagus racemosus	Adaptogenic drugs may promote the balance of estrogen and progesterone and follicular growth	500-1500 mg of traditional root extract each day	Conventional ayurvedic application; little clinical PCOS data.	[52]
9.	Turmeric / Curcumin	Curcuma longa	Anti - inflammatory, perhaps improving metabolic parameters and	500-1000 milligrams of curcumin per day diet (supplement)	Meta -analysis point to metabolic advantages; curcuminoids	[53]

			insulin resistance		gain most form standardization.	
10.	Spearmint	Mentha spicata	May clinically diminish testosterone levels (supporting hirsutism)	Tea (one to two cups each day) or extract according to the package label	Supportive herb; evidence primarily for androgen effects rather than direct PCOS studies.	[54]

Table 2. Herbal drugs used in PCOS management with their MOA, typical dosage and key effects.

Synthetic Drug Treatment for Management of PCOS

Metformin (Glucophage)

Metformin, a biguanide substance, inhibits the synthesis of glucose in the liver, reduces intestinal glucose absorption, and enhances insulin sensitivity in skeletal muscles and adipose tissues [55]. Metformin was proven to improve fertility, pregnancy, and ovulation outcomes in women with PCOS when compared to a placebo group [56].

Thiazolidinedione

This medication is a thiazolidinedione drug that stimulates PPAR-γ [57]. It affects peripheral absorption of glucose, adipogenesis, and insulin sensitivity [58]. Pioglitazone may reduce high cholesterol and reduce cardiovascular risk [59]. A 2020 study by Rana et al. found that pioglitazone therapy for three consecutive cycles resulted in 44% ovulation success and a 20% increase in conception rate [60].

Glucagon like peptide -1 agonists

A class of antidiabetic drugs named glucagon-like peptide-1 (GLP-1) agonists has effects similar for people of intestines [61]. Exenatide and liraglutide, two GLP-1 agonists, have been evaluated for PCOS treatment. Liraglutide can be used for reducing insulin resistance and metabolic dysregulation with subsequent CVD risk in females with PCOS, in accordance to a 2022 study by Krzysztof et al. Also, this type of medication can improve ovulatory cycles and metabolic functions [62]. But a 2020 study by Georgios S. et al. discovered that liraglutide significantly reduced body weight, BMI, and abdominal circumference. It also improved SHBG and reduced serum testosterone in obese female PCOS patients [63].

Dipeptidyl peptidase 4 (DPP-4) inhibitors

Are also an innovative class of antidiabetic drugs that may help regulate blood sugar by increasing the concentration of incretin, which enhances the action of insulin. As a result, these medications may have a new potential to be used in PCOS [64]. More than three DDP-4 inhibitors have been evaluated for the treatment of PCOS: sitagliptin, linagliptin, and valdigliptin. These medications may improve glucose tolerance and the function of the pancreatic beta cells [65]. In a 2018 study, Simona F et al. found that sitagliptin improved the results of the HOMA test as well as beta cell activity [66].

Sodium glucose cotransporter -2 inhibitors

A type of anti-diabetic medicine known as sodium glucose cotransporter-2 (SGLT-2) inhibitors has a unique mechanism that regulates blood glucose levels by glycosuria in addition to its respiratory impact. As a result,

these agents inhibit renal glucose reabsorption in renal proximal tubules. Four SGLT-2 inhibitors, including empagliflozin, licogliflozin , and dapagliflozin — have been examined in PCOS [67].

Melatonin

Also, melatonin might have an anti-androgenic effect by decreasing the production of testosterone [68]. As well, melatonin increases physiological indicators like insulin resistance, blood glucose, and lipid profile [69]. Melatonin treatment for three weeks enhanced insulin sensitivity, the homeostasis model of assessment insulin resistance (HOMA-IR), and the total lipid profile, including low-density lipoprotein (LDL) levels, as per a 2019 study by Shabani A. et al. [70].

Advanced Technologies in Management of PCOS

PCOS precision medicine and customized treatment strategies

Through providing individualized, accurate, and precision-based treatment, advanced technologies are gradually altering how polycystic ovarian syndrome is controlled. Early diagnosis, improved profiling, and specific treatment interventions have been made available by the integration of electronic medical tools, omics technologies, and modern reproductive methods. These advances could improve long-term metabolic and reproductive outcome while managing the wide range of PCOS [71].

Wearable technology and digital health technologies for tracking symptoms and lifestyle

By monitoring physical activity, nutrition, sleep, and menstrual cycles in real time, digital health technologies such as wearable technology and mobile health (mHealth) apps— assist with lifestyle change. By identifying ovulatory patterns, insulin resistance risk, and therapy response, artificial intelligence-based algorithms included in these platforms may enhance consumer engagement and adherence to personalized treatments [72].

Technologies based on omics to comprehend the molecular pathophysiology of PCOS

The molecular pathophysiology of PCOS has been clarified thanks to omics-based tools such proteomics, metabolomics, and gene databases. These techniques make it simpler to discover new biomarkers for inflammation, high testosterone levels, and insulin resistance. This allows patients to be categorized into different phenotypes and supports treatment decision-making based on targeted therapy [73].

Modern assisted reproductive Technologies for the treatment of PCOS

Advanced assisted reproductive technologies (ART) have significantly enhanced fertility results for women with PCOS in reproductive management. These technologies include time-lapse embryo imaging, preimplantation genetic testing, and customized ovarian stimulation protocols. Future PCOS treatments solutions could also benefit from modern innovations like gut microbiome adaptation and machine learning-guided treatment optimization [74].

Platforms for virtual care and telemedicine for Long-term PCOS management

Telemedicine and virtual care platforms have shown themselves to be useful tools for the long-term management of PCOS, especially when it comes to expanding access to multidisciplinary care between endocrinologists, gynecologists, nutritionists, and mental health specialists. Particularly in environments with scarce assets, remote consultations in conjunction with digital monitoring of metabolic and reproductive parameters offer continuous tracking, early intervention, and better treatment adherence [75].

PCOS diagnosis and risk prediction using artificial intelligence and machine learning

PCOS diagnosis and risk assessment have begun to utilize machine learning and artificial intelligence (AI) technology. AI-based models predict insulin resistance, cardiovascular risk, and infertility outcomes more accurately than traditional techniques by analyzing clinical, biochemical, and imaging data.

Individualized treatment planning based on patient-specific risk profiles is made practicable by these technologies, as they also improve early identification [76].

Cutting -edge imaging technologies for ovarian morphological Evaluation

The accuracy of ovarian morphological assessment in PCOS can be enhanced via advanced imaging technologies, which include automated follicle counting instruments and three-dimensional transvaginal ultrasonography. These methods improve diagnostic consistency and treatment response monitoring by reducing inter-observer variability and providing accurate assessment of follicle number and ovarian volume [77].

Gut microbiome -based technologies in PCOS treatment

The involvement of gut dysbiosis in the pathophysiology of PCOS has been made known by an increasing curiosity in microbiome-based technologies. Metagenomic and high-throughput sequencing studies have identified changes in gut microbial composition correlated with hyperandrogenism and insulin resistance. Precision probiotics and fecal microbiota transplantation are two examples of microbiota-targeted therapies being researched as new methods of treatment [78].

Ayurvedic Perspective on PCOS

Providing an ancient heritage spanning thousands of years, Ayurvedic medicine is an old systemic strategy that developed in India. "Ayurveda," that finds an origin in Sanskrit, means "knowledge of life. "Primarily, Ayurveda emphasizes that the foundation of health and well-being is the delicate balance of all three parts of the body. Herbal treatment, food recommendations, yoga, meditation, and detoxification methods are only some of the various fields included in this traditional medical strategy. Due to research, Ayurvedic treatments have the potential to treat a wide range of conditions, particularly lifestyle-related disorders, mental health problems, and chronic diseases [79]. According to Ayurveda, Vata and Kapha dosha imbalances are the main cause of PCOS, which is linked to Yonivyapad and Artavadushti. PCOS is thought to be largely caused by unhealthy eating habits (Mithyaahara) and lifestyle factors (Mithyavihar), such as stress, insufficient sleep, and obesity [80]. Vata, Pitta, and Kapha are the three basic factors that control bodily activities, according to Ayurveda's Tridosha theory. Pitta governs digestion and metabolism, Kapha preserves growth, structure, and stability, while Vata governs mobility and communication. The balance of these doshas, which are drawn from the five elements—Air, Water, Fire, Earth, and Space—determines each person's distinct Prakriti (constitution) [81]. Herbs like Manjistha and Ashoka for hirsutism and Neem and Kutki for acne are used to treat pitta vitiation, which causes hirsutism, acne, and heart disease. Treatments such as enemas made with triphala for obesity address kapha vitiation, leading to weight gain, cyst growth, and depression. Ayurvedic treatments for Aartava-kshaya, which is associated with PCOS, focus on regulating metabolism, reducing pelvic cavity disorders, and establishing balance to the menstrual system (Airwave Dhatu). The therapy concepts seek to restore equilibrium among Dosha, Dhatu, and Upadhatu while taking into account specific indications associated with Kapha, Pitta, and Vata predominance [82]. It is crucial to adjust the treatment strategy according to each patient's symptoms while keeping Nidana Parivarjana (avoidance of disease-causing variables) in mind. Women are advised to adhere to concepts like Dincharya (daily regimen), Ritucharya (seasonal regimen), Sadvritta, Achara Rasayana, Hitahara, Samyaka Nidra (appropriate sleep), and Vyayama (physical exercise) in order to prevent the onset of the disease. PCOS is treated with panchakarma, an integrated Ayurvedic treatment [83]. Prakruti, Vikruti, Dosha, Dushya, Agni, and Ama are the foundations of Ayurvedic PCOS treatment. In women with PCOS, herbal therapies like Meshshringi, Shatavari, Methika, Kumari, Lodhra, and Jatamamshi have been proven to improve insulin sensitivity, ovulation, hormonal balance, reduce ovarian cysts, and lower androgen levels [84].

DISCUSSION

It is becoming more well acknowledged that polycystic ovarian syndrome (PCOS) is more than just a reproductive failure; it is A complicated, long–term endocrine-metabolic illness.[85] The multifaceted etiology of PCOS is highlighted in this review, which also emphasizes the significance of a comprehensive therapeutic strategy that incorporates medication, and physiological health, like a strategy is crucial [86]. The important

involvement of insulin resistance (IR) in the pathophysiology of PCOS is a crucial discovery that is highlighted across the article .Reproductive abnormalities and metabolic conditions are closely linked with insulin resistance .In addition to lowering sex hormone-binding globulin (SHBG) hyperinsulinemia increase circulating free androgens via stimulating ovarian theca cells to increase androgen production .This hormone imbalance causes irregular menstruation, infertility, and persistent anovulation by interfering with follicular development. Crucially, insulin resistance is seen in both lean and obese women with PCOS, highlighting the necessity of metabolic assessment regardless of BMI Targeting insulin sensitivity as the main treatment objective has a molecular foundation because of the intrinsic changes [87]. While traditional insulin –responsive medication like metformin is still essential there is mounting evidence that nutraceuticals can be used as an adjuvant to more safely modify this biological process over time [88]. Women with PCOS frequently have vitamin D deficiency, which is linked to increased androgen production, insulin resistance, irregular menstruation, and infertility. Supplementing with vitamin D may enhance reproductive and metabolic outcomes, especially in those who are deficient [89]. Although clinical outcomes vary, improved menstrual regularities and ovulatory potential have frequently been observed following deficiency correction. Supplementing with insitols, especially myo-insitol and D-chiro-insitol, is one of the most thoroughly studied nutraceutical therapies for PCOS. By functioning as an insulin second messenger, they increase insulin sensitivity, lower elevated glucose levels, and indirectly reduce ovarian androgen synthesis [90]. Dietary changes continue to be a crucial part of PCOS management. Low-glycemic index diets, balanced macronutrient intake, and anti-inflammatory dietary patterns like the Mediterranean diet have consistently reduced insulin resistance, lipid profiles, and circadian rhythms [91,92]. For overweight women with PCOS, even a little amount of weight loss by dietary change can improve menstrual regularity and reinstate ovulation. To guarantee devotion and long-term durability, customized dietary strategies [93]. Insulin resistance and ovarian dysfunction in PCOS are caused by oxidative damage and persistent low-grade inflammation. Insulin sensitivity, ovarian function, and reproductive outcomes may be enhanced by antioxidant nutraceuticals such N-acetylcysteine, coenzyme Q10, vitamins C and E, omega-3 fatty acids, and herbal substances like berberine, cinnamon, and curcumin [94,95]. In example berberine has insulin –sensitizing properties similar to those of metformin and might be a useful substitute for women who are intolerant of traditional drugs. When added to conventional medications, these botanicals provide metabolic, anti-inflammatory and antioxidant advantages [96]. In addition, a complete and long-lasting strategy can be achieved by combining traditional pharmaceutical therapy and lifestyle change with nutraceuticals, dietary interventions, antioxidants, and herbal remedies. In the end this combined approach improves long-term health outcomes and quality of life for women with PCOS by addressing both symptom management and root cause of biochemical and autoimmune conditions.[97]

CONCLUSION

Polycystic ovarian syndrome (PCOS) is a multisystem disorder caused mostly by insulin resistance, which increases androgen production, lowers SHBG levels, and results in anovulation, irregular menstruation, infertility, and polycystic ovarian morphology. PCOS occurs at all body weights and is caused by genetic, environmental, inflammatory, and gut microbial variables. Micronutrient deficiencies, especially vitamin D insufficiency, and decreased inositol metabolism exacerbate insulin resistance and hormonal imbalance. Long-term, customized care that includes lifestyle modifications, medication, nutritional assistance, and psychosocial therapies is required for effective management.

Future Perspectives

Future perspectives include precision medicine techniques, further research of gut microbiota modification, targeted micronutrient treatments, and early preventive measures to improve long-term metabolic and reproductive outcomes.

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