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Nutritional and herbal interventions for polycystic ovary syndrome (PCOS): a comprehensive review of dietary approaches, macronutrient impact, and herbal medicine in management

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Abstract

Polycystic Ovary Syndrome (PCOS) is a common health condition related to a woman's hormonal problems. Hormonal imbalance, metabolic disorders, and an increased insulin level mainly characterize the ailment. This detailed review focuses on dietary strategies, macromolecules, macromolecules, and herbal interventions that exception-ally work in PCOS treatment. Research has shown that Mediterranean, low-glycemic index, and ketogenic diets that are modified with individuals in mind are the best ways to resolve insulin resistance, obesity, and lack of ovulation. The other nutrients shown to affect glucose metabolism and play a role in hormone regulation are the macromolecules, such as increased protein and reduced refined carbs. Among the different micronutrients, vitamin D, omega-3 fatty acids, and inositol were shown to be the most vital supplements in the treatment of PCOS-induced oxidative damage, hyperandrogenism, and infertility. Not to mention, cinnamon, curcumin, sage, fennel, and traditional Chinese herbal medicine are among some of the herbal remedies that so far show good potential to be the perfect complementary therapy tools as they create better glycemic control, inflammation reduction, and menstrual cycle regularization. Even though the findings are promising, the current supply of clinical trials for standardizing these nutritional and herbal protocols is lacking. Overall, this report stresses the fact that a customized, holistic diet regime is the best treatment for women with PCOS to make them feel well and live a long and healthy life.

Keywords Nutrition, Macronutrients and micronutrients, Metabolic syndrome, Insulin resistance, Reproductive health, Endocrine disorders

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Introduction

Polycystic Ovary Syndrome (PCOS) is a prevalent endocrine disorder, affecting approximately 18% of women of reproductive age globally [1]. It manifests as a complex condition involving reproductive, metabolic, and psychological challenges, making diagnosis and management difficult [2]. According to the Rotterdam criteria, PCOS is diagnosed when at least two of the following are present: hyperandrogenism, ovulatory dysfunction, and polycystic ovarian morphology [3]. Despite significant research efforts, the exact cause of PCOS remains unclear, although genetics, environmental influences, and lifestyle factors are believed to play key roles [4]. Insulin resistance, obesity, and chronic low-grade inflammation are commonly associated with PCOS and contribute to its progression [5]. Insulin resistance worsens hyperandrogenism, leading to clinical features such as hirsutism, acne, and alopecia. Additionally, hyperinsulinemia disrupts ovarian function, leading to anovulation and infertility. Women with PCOS are also at higher risk for metabolic complications, including type 2 diabetes, dyslipidemia, and cardiovascular disease [6]. Obesity further amplifies these risks by promoting inflammation and hormonal imbalance [7]. Given its multifactorial nature, PCOS management requires a multidisciplinary approach. Lifestyle and dietary interventions are central to treatment, as they directly influence metabolic and endocrine pathways [8, 9]. Specific dietary patterns, such as low-glycemic index (GI), Mediterranean, and ketogenic diets, have shown promise in improving insulin sensitivity and hormonal balance in PCOS [10–12].

Low-GI diets focus on whole grains, legumes, and fiber-rich foods, which help stabilize blood glucose levels and support ovulation [10, 11]. The Mediterranean diet emphasizes anti-inflammatory foods like fruits, vegetables, healthy fats, and lean proteins, contributing to improved cardiovascular and hormonal health. The ketogenic diet, characterized by low carbohydrate intake, promotes weight loss and enhances insulin sensitivity—key outcomes in PCOS management [13, 14]. Macronutrient composition is another essential element. High-protein and low-carbohydrate diets improve satiety, preserve muscle mass, and reduce insulin resistance and hyperandrogenism [15, 16]. Research suggests that reduced carbohydrate intake, specifically complex carbohydrates, is more effective for blood sugar levels and metabolic outcomes in women with PCOS [17, 18]. Dietary fat quality also has a significant influence, with unsaturated fats, particularly omega-3 fatty acids, exhibiting anti-inflammatory and insulin-sensitizing effects [19]. Conversely, an overabundance of saturated fat has been associated with amplified androgen levels and metabolic disorders in PCOS [20]. Micronutrient deficiencies prevail in cases of Polycystic Ovary Syndrome among women and might be the cause of the progression of the disease [21]. Essential nutrients, including vitamin D, niacin, and magnesium, are some examples of such nutrients that have been investigated for their affirmative healing effects [22]. Vitamin D deficiency is more common in women with PCOS and is related to insulin resistance, ovulatory dysfunction, and infertility [23]. Supplementation with vitamin D has been shown to improve insulin sensitivity, menstrual regularity, and fertility outcomes [24]. Inositol, a naturally occurring sugar alcohol, is one of the compounds that caught the eyes of the researchers and thus became a subject of intense publicity because it has a structure that closely resembles insulin and, thus, can increase insulin sensitivity and, finally, can improve ovarian function. Myo-inositol and D-chiro-inositol supplementation were shown to have a beneficial effect by helping women with PCOS to become ovulatory, also to balance hormones, and restore metabolic health in PCOS (polycystic ovary syndrome) patients [25]. Regarding improved insulin sensitivity and inflammation reduction, magnesium, an essential micronutrient, has been shown to be an important part of nutritional therapy in PCOS [26]. Beyond conventional dietary interventions, herbal medicine has assumed the role of a promising supplementary approach for PCOS [27, 28]. Some different types of herbs, such as cinnamon, curcumin, sage, and fennel, have been the subject of extensive research regarding their potential to improve metabolic health and fertility [29]. Being a widely used spice, cinnamon has been found that it can lower sugar levels by improving the efficiency of insulin and glucose intake [30]. The meta-analysis of clinical trials has determined that the pos of cinnamon supplements blood glucose, whether fasting insulin and other insulin resistance markers in women with PCOS, showed improvement [31]. Due to the anti-inflammatory and antioxidant characteristics of the active part of turmeric, called curcumin, they may be helpful in the improvement of PCOS [32]. Clinical research has shown that taking the curcumin supplement can improve insulin sensitivity and also lower the androgen levels of women with PCOS [33]. Sage, which has been traditionally used in Iranian medicine, was found to restore insulin sensitivity and reduce BMI in PCOS patients [34]. Moreover, fennel is a phytoestrogen and has been studied to recognize its potential to regulate menstrual cycles and improve metabolic health in women with PCOS [35].

This review emphasizes the importance of dietary strategies, the role of macro- and micronutrient balance, and herbal medicine's potential in managing PCOS. Behavioral interventions, particularly those involving diet and physical activity, should focus on managing this multifaceted condition. Existing evidence supports the crucial role of nutrition in both the prevention and treatment of PCOS-related symptoms. However, additional research

is needed to standardize dietary approaches and personalize treatment plans based on individual metabolic profiles. By deepening our understanding of the dietary and lifestyle factors influencing PCOS, we can develop more targeted interventions to enhance the quality of life for affected women. Therefore, this review aims to provide a comprehensive synthesis of current dietary strategies, macronutrient and micronutrient interventions, and herbal therapies for the management of PCOS. By highlighting established and emerging approaches, this review aims to support the development of individualized, evidence-based treatment frameworks to improve metabolic and reproductive outcomes.

Adolescent polycystic ovarian syndrome

PCOS, which is short for polycystic ovarian syndrome, is a complex and diverse disease that affects young and middle-aged women. Figure 1 PCOS symptoms can be seen in youngsters. Even if the disease is widespread, information regarding this can be lacking; thus, understanding the genesis and development of polycystic ovarian syndrome is not so clear [36]. A delicate balance between dormant and actively developing follicles, regulating factors that influence follicular growth, and selecting one follicle for mature ovulation define the ovaries' anatomy and physiology [37]. Androgen, anti-Müllerian hormone (AMH), and follicle-stimulating hormone (FSH) levels are all over the place in PCOS-affected adolescents. When follicles mature, the body produces more androgens due to increased relative luteinizing hormone (LH) [38]. Follicular development comes to a standstill, and androgen conversion to estradiol slows down due to inadequate FSH output. Many teenagers with polycystic ovary syndrome have insulin resistance and high insulin levels [39]. Be aware that these factors have been linked to an increase in androgenize. This occurs because the pituitary gland and adipose tissue are stimulated to produce androgens and luteinizing hormone, respectively, in response to increasing levels of androgens, which in turn heighten insulin resistance (IR) and hyperinsulinemia (Hg).

Since polycystic ovarian syndrome (PCOS) affects girls who are at risk for the disorder, especially individuals who are overweight, have early pubarche, or are PCOSd (daughters of women having PCOS), a great deal of research has focused on the pubertal ontogeny of PCOS

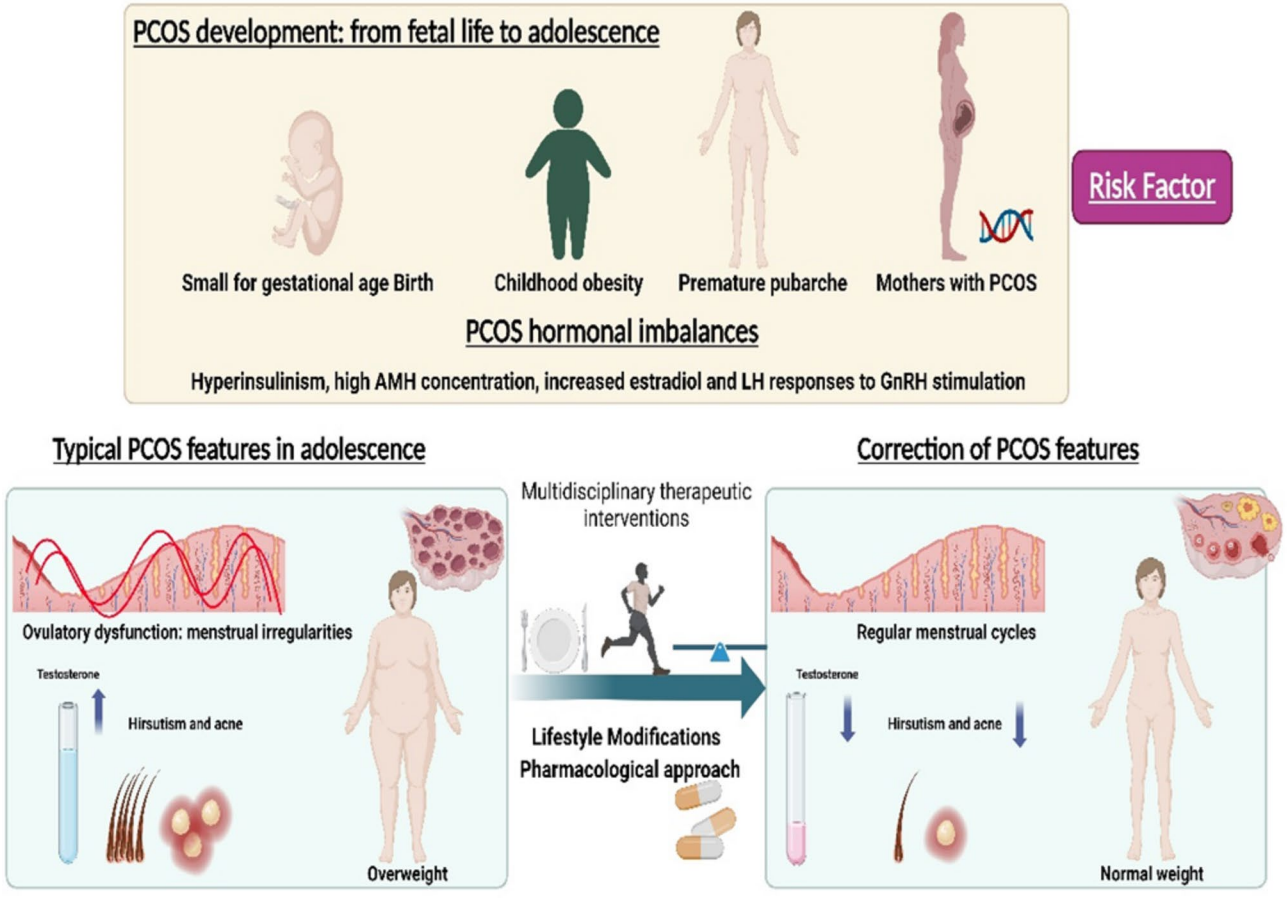

Fig. 1 The stages of polycystic ovarian syndrome: infancy to puberty

[40]. In one investigation, AMH, insulin, and androgen levels were more significant in PCOS daughters than in regular participants [41]. The metabolic features of polycystic ovarian syndrome, or PCOS, include an enlarged ovary and increased estradiol and LH sensitivity to gonadotropin-releasing hormone, or GnRH. Throughout puberty and the post-pubertal period, girls with polycystic ovarian syndrome, a hallmark of adrenarche, experienced symptoms like PCOS, which were linked to acute stimulation of the gonadotropin-releasing hormone (GnRH).

The symptoms that were listed (oligomenorrhea, hirsutism, biochemical and functional hyperandrogenism, etc.) were hyperandrogenism and others. The AMH models showed that the AMH levels were also high in the girls with PP. It was thought that due to the high insulin concentration, the adrenal and the ovary would produce more androgen than usual, causing PCOS to be a part of PCOS [42]. PCOS, a fertility issue that frequently happens to women, is a frequent one. It is a fact that several factors, including anovulation, menstrual irregularities, and infertility, influence the disorder. Moreover, acne and a high amount of insulin in the body's blood are sequential events [43]. Figure 2 is a summary of the different treatments that cause ovulation and the management of infertility in PCOS patients with symptoms such as obesity, insulin resistance, hirsutism, and acne. A hormonal contraceptive drug, the most recommended first-line treatment for anovulation, metformin comes in second place on the list. In infertility cases, clomiphene or letrozole are the initial remedies suggested [44]. Fighting obesity and insulin resistance can be achieved with the help of weight loss programs, daily workouts, food habit adjustments, and a stress-free lifestyle that bestows insulin sensitivity and hormonal equilibrium, thus bringing them to a lower degree [45]. Clinical symptoms such as hirsutism and acne have a very wide range of symptoms and treatment therapies. Specific cosmetic and pharmacological therapies are essential in treating these symptoms, along with light-based treatments, topical creams, and anti-androgen drugs [46]. This personalized treatment approach focuses on both systemic and symptom-specific aspects of PCOS to enable better reproductive and metabolic health [47].

PCOS is a problematic issue that is related to multiple systemic problems, including insulin resistance, hyperandrogenism, and metabolic disorders, all of which contribute to different symptoms like acne, alopecia, and hirsutism Fig. 3. The androgen signature is enhanced by the insulin outputs obtained through the PI3K-AKT-mTOR pathway, and in turn, the symptoms are amplified. Furthermore, an altered bone metabolism that is caused by androgen excess is evident in PCOS. Imbalance in the OPG and RANKL properties is directly associated with the differentiation and activity of osteoclasts and favors bone resorption. On the other hand, the decrease in Trap5b breaks the balance of osteoclast fusion, and instead, there is an increased osteoclast fusion, which in turn enhances the risk of osteoporosis in women with PCOS. This indicates the need for a comprehensive

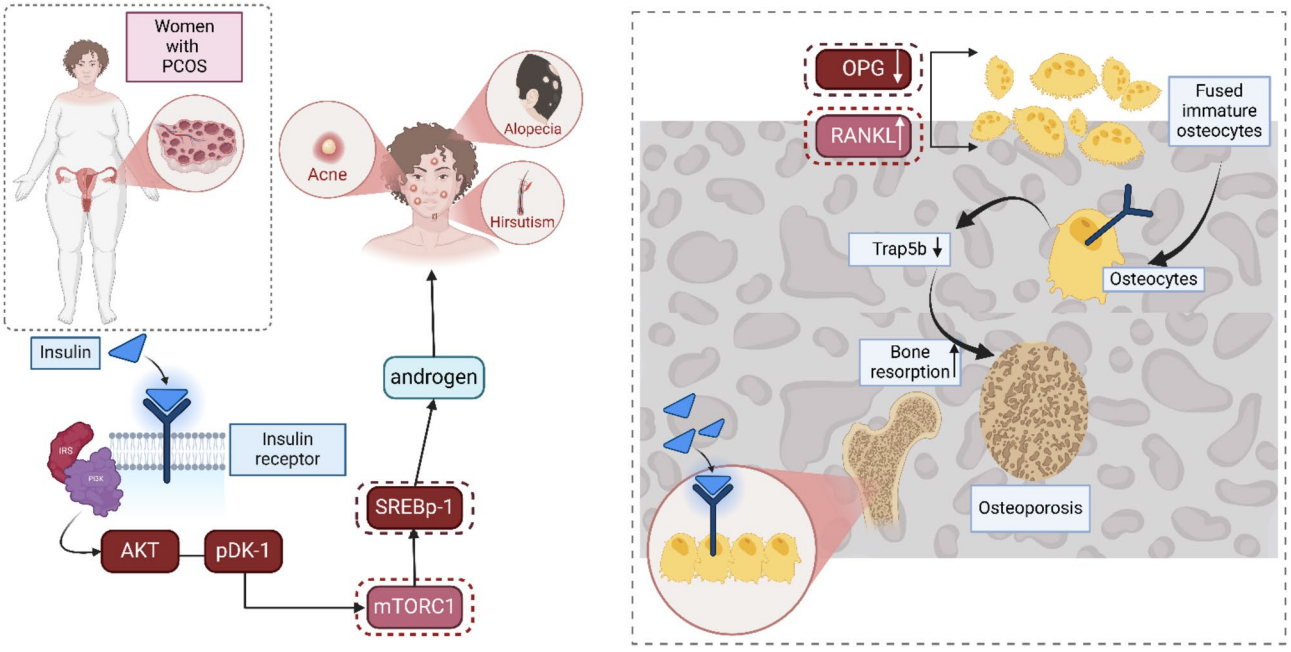

Fig. 2 PCOS, insulin signaling, androgen production, and bone metabolism molecular pathways. The left panel shows how insulin resistance and androgen excess cause acne, alopecia, and hirsutism in PCOS. The right panel shows how RANKL, OPG, and Trap5b change osteoclast activity and bone resorption, causing osteoporosis

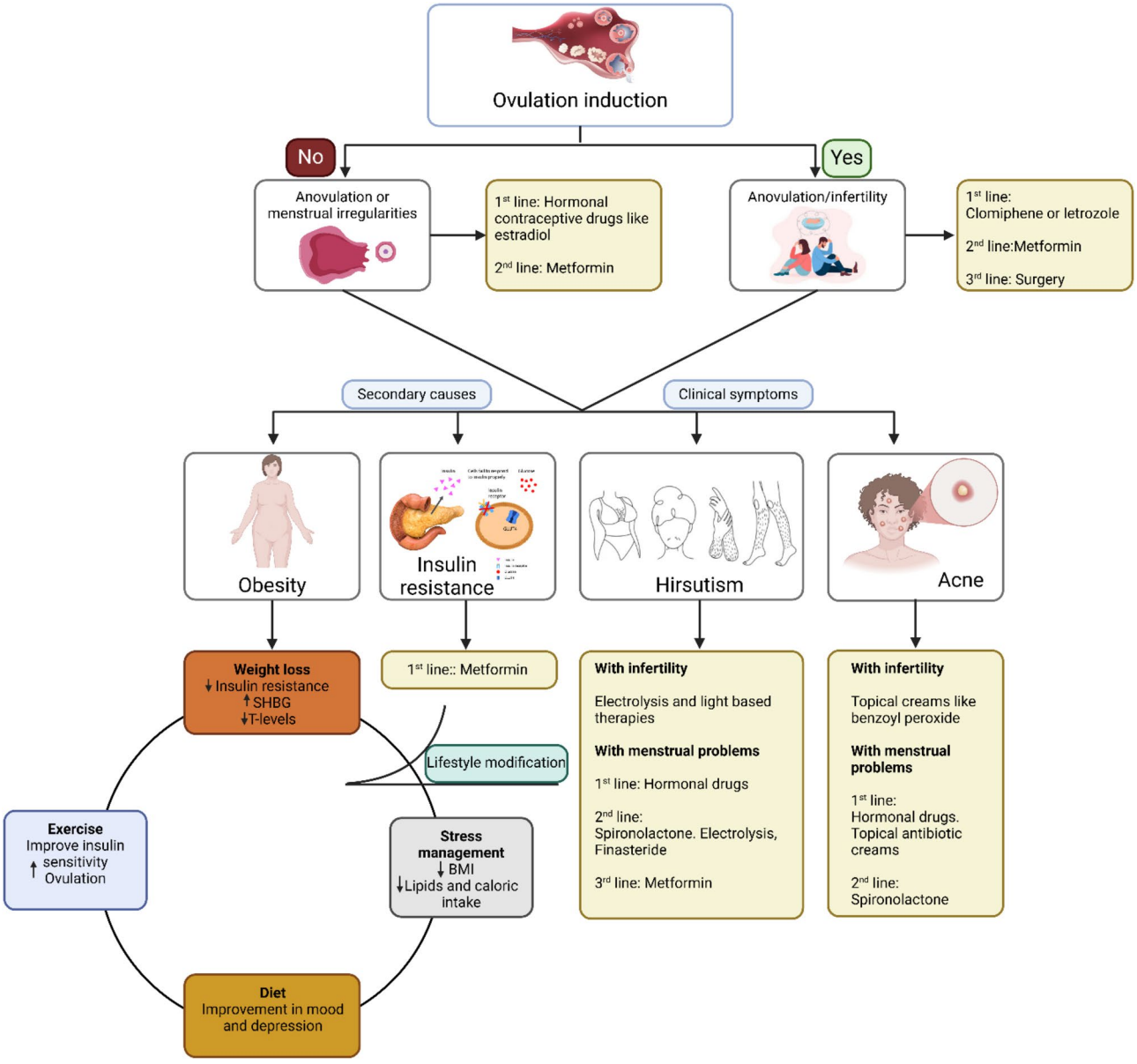

Fig. 3 Comprehensive approach to ovulation induction and the management of associated clinical symptoms in PCOS. The diagram delineates primary and secondary causes, clinical symptoms, and corresponding therapeutic interventions, including pharmacological, lifestyle, and cosmetic treatments

treatment strategy, including managing PCOS metabolic and skeletal appropriate [48].

Interlinking between obesity and insulin resistance in PCOS

Insulin resistance (IR) is a health issue described by a diminished ability of external or internal insulin to effectively promote the intake and utilization of glucose in comparison to a regular group [49]. Insulin resistance refers to a condition where peripheral tissues show decreased sensitivity to insulin actions, requiring larger hormone doses to regulate glucose levels within the normal range. Compensatory hyperinsulinemia, which is commonly observed in individuals with PCOS [49–51], significantly contributes to the progression of the disorder. Insulin resistance is seen in around 44–70% of women who have been identified with PCOS [52]. Moreover, women who have both obesity and PCOS exhibit a greater level of insulin resistance in comparison to obese persons who do not have PCOS [53]. These findings indicate that PCOS and obesity affect insulin sensitivity, and their coexistence might worsen insulin resistance. An investigation conducted by DeUgarte and colleagues found that 64.4% of patients diagnosed with PCOS, also referred to as displayed insulin resistance. Patients with insulin resistance (IR) exhibited higher body mass

indexes (BMIs); PCOS women with insulin resistance have a higher accumulation of visceral fat, a surplus of androgens and experience more severe clinical symptoms, including hirsutism, acne, and ovulatory disorder, in contrast to PCOS women lacking insulin resistance [54].

Insulin governs developmental processes and exerts influence on ovarian physiology as well as pathology [49, 55]. Insulin receptors are present in both stromal and follicular cells in the ovaries, and they contribute to the formation of follicles and the production of ovarian steroids [55]. Hyperinsulinemia, which refers to abnormally high amounts of insulin in the bloodstream, can lead to an elevation in the synthesis of androgens. Consequently, this can impede the body's capacity to react to insulin efficiently [56]. PCOS is defined by the presence of reproductive and metabolic issues, which are caused and worsened by this detrimental cycle. The occurrence of ovulation appears to rely on the pivotal function of signaling by insulin in the brain and nervous system. Hyperinsulinemia can interfere with the signaling of GnRH, resulting in higher levels of LH and more frequent and intense GnRH pulses [57]. Obesity can worsen low-grade inflammation, which can, in turn, lead to neuroendocrine dysfunction. This inflammation can also occur in the central nervous system [58].

Insulin also affects the synthesis of adrenal androgens [59]. Approximately 20–30% of women who are identified with polycystic ovarian syndrome exhibit increased levels of dehydroepiandrosterone (DHEA) and DHEAS [60]. Individuals diagnosed with polycystic ovary syndrome may show increased production of adrenal steroids in reactions to adrenocorticotrophic hormone (ACTH) [61]. The correlation between DHEAS levels and IR in women with PCOS seems logical, as these levels decrease with medication that enhances insulin sensitivity [62]. Insulin resistance (IR) is not the leading cause of obesity, although obesity really does worsen the insulin resistance of polycystic ovarian syndrome (PCOS) and hyperandrogenemia. Hyperinsulinism can appear due to insulin resistance and be caused by the production of chemical substances that are metabolically active by the visceral adipose tissue [63].

Nutrients and PCOS

PCOS is a common endocrine disorder that is mainly observed in women of childbearing age and is characterized by various symptoms such as irregular menstrual cycles, hyperandrogenism, and ovarian dysfunction. Some reports suggest that the intake of the proper nutrients can have a very big effect on the symptoms and metabolic complications of PCOS. Lack of macronutrients and micronutrients has been found to lead to either worsening or improving the PCOS condition when associated with bad dietary habits. Nutrient patterns that are rich in vitamins, minerals, fiber, and healthy fats are beneficial in the treatment of PCOS. By way of illustration, Eslamian and Hekmatdoost proved that the occurrence of PCOS can be decreased with riboflavin, niacin, the vitamins C, D, E, and K, fiber, and polyunsaturated fatty acids found to be in the diet. On the contrary, those who will have diets with a higher level of saturated fats, cholesterol, and sodium than the standard, if not the diets that are standard, will have higher chances of having PCOS [64]. Micronutrient deficiencies are frequently identified among women with PCOS, making it androgenic to the pathophysiology of PCOS. Mansour et al. pointed out that inositol, omega-3 fatty acids, vitamin D, and resveratrol increase hormonal balance and insulin sensitivity in PCOS patients [65]. Equally, Dubey et al. examined the function of vitamins and antioxidants in alleviating oxidative stress, a general actor in PCOS pathophysiology [66]. Vitamin D is one of the vital micronutrients. Lack of it is common in women with PCOS and has a connection with insulin resistance, ovulatory issues, and infertility. A study has shown that the administration of vitamin D led to improved fertility and ovulation rates in women with PCOS whose vitamins are insufficient [67]. By the same token, omega-3 fatty acids, which are exceptional at reducing inflammation, have been proven to be beneficial with reference to metabolic parameters and related effects on PCOS risk [68]. Other essential nutrients include folate, vitamin B12, calcium, and zinc. A deficiency in these nutrients has been linked to mental health symptoms such as anxiety and depression, which are not solely explained by insulin resistance. Addressing these deficiencies can improve learning outcomes for women with PCOS [69].

Macronutrients, for instance, carbohydrates, sugars and fats. Proteins, for example, Influence the functions of all three similarly. To be more specific, Carbohydrates control glucose resistance and metabolic conditions. Low glycemic index foods with sufficient proteins and fibers have shown a positive trend in Bieber's sensitivity and dropped androgen levels [70]. Omega-3s, embedded in the environment of a keto or Mediterranean eating plan, have been connected to body fat reduction and higher insulin sensitivity, which are the main aspects of PCOS treatment [71]. Nutrient intake guidelines underscore the necessity of having macronutrients and micronutrients in balanced proportions for a healthy body. Carbohydrates, fats, and proteins, as examples of macronutrients, are needed in high quantities for energy creation and dissection of tissues/repairing tissues [72]. However, micronutrients such as vitamins and minerals are the most essential things used in cells to get in touch with the nerves and keep the arteries healthy [73]. Both deficiencies and overconsumption of nutrients can cause health

problems, so the need for a balanced dietary approach is severe [74]. In conclusion, nutrients are essential in overcoming PCOS by balancing the hormones, oxidative stress, and insulin resistance. By introducing more omega-3 fatty acids, vitamin D, and antioxidants to the dietary regime and, at the same time, making the necessary macronutrient changes like the reduction of the intake of saturated fats and carbohydrates, successful management of symptoms and metabolic health improvement is expected. A balanced diet with ample fiber, vitamins, and monounsaturated fats is the most reliable method for treating women with PCOS.

Macronutrient

These are required in large amounts and include carbohydrates, proteins, and fats/oils.

Impact of carbohydrates on PCOS

PCOS is intricately linked to carbohydrate metabolism, with both the type and amount of carbohydrates consumed significantly influencing its symptoms and metabolic profile. Dietary carbohydrate intake affects insulin resistance, inflammation, weight regulation, and hormonal balance, critical components of PCOS pathology.

Reducing carbohydrate intake has demonstrated significant benefits for PCOS management. For example, an LCKD (low-carbohydrate, ketogenic diet) is an effective method for losing weight, improvement of fasting insulin as well as free testosterone levels in obese and overweight women with PCOS. During the process of the study, on average, insulin sensitivity was strongly enhanced, and in some cases, some women even became fertile again [75]. Also, an analysis by meta-analysis of controlled trials has shown that low-carb diets have a significant impact on BMI, HOMA-IR (insulin resistance), and cholesterol content, especially when interventions last more than four weeks [76].

Eating a lot of carbohydrates, especially from processed products with a high GI, is the reason for increased insulin resistance along with systemic inflammation, which is the regular result of PCOS. The high amounts of sugar in the blood caused by the above diet increase oxidative stress, which raises the reactive oxygen species, creating a declining insulin sensitivity in the long term [77]. Insulin resistance is at the core of PCOS, which leads to hyperandrogenism and problems with ovulation. Carbohydrate intake, when controlled, is a good way to lessen these harmful effects to the maximum.

Research points to the fact that the best way of dealing with PCOS is through diet changes that focus on the reduction of carbohydrates and the addition of protein and fat. For example, a diet that was very low in starch was found to amplify the fat-burning mechanism and lessen fasting insulin. The woman on this diet gained less around her tummy during these weeks than the standard diet participant, which attests to the effectiveness of the low-starch, low-dairy diet for PCOS-related metabolic impairment [78].

Carbohydrate restriction's effectiveness in ameliorating reproductive health in PCOS patients is also impressive. A trial that associated a low-carbohydrate diet with metformin and moderate exercise found that the patients who lost weight improved glucose metabolism and increased the incidence of natural pregnancy among obese females with PCOS [79]. These new approaches serve as the fundamental ground for whole carbohydrate control as cortisol shortens both metabolic and reproductive signals in PCOS.

Insulin resistance in PCOS is like the metabolic dysfunction noted in type 2 diabetes. Women with PCOS are inclined to incur a higher chance of type 2 diabetes aside from the ones caused by cardiovascular disease because of the application of high-carbohydrate diets, which exacerbate insulin resistance. In other words, Low-GI foods and carbohydrate restriction are thus recommended as first-line interventions to manage PCOS and prevent associated long-term complications [80].

A low-carbohydrate diet serving 43% of total caloric intake over 16 days resulted in notable decreases in fasting and post-exercise insulin levels, implying a promising short-term dietary manipulation [81]. Gradual implementation of this approach may further enhance reproductive and endocrine outcomes in women with PCOS. A study by Marsh et al. compared a typical high-calorie diet with a low-GI diet among 96 women with PCOS. While both diets were low in calories and fat, only the low-GI diet improved overall insulin sensitivity, fibrinogen levels (an inflammatory protein), and menstrual regularity, highlighting its superior metabolic benefits.

Unlike carbohydrates from non-starchy vegetables and fruits, dairy products and starchy foods trigger higher postprandial insulin release. In an eight-week intervention, women with PCOS who reduced their intake of dairy and carbohydrates experienced improved lipid oxidation and metabolic outcomes [78]. Eslamian et al. also observed that women with PCOS had higher dietary GI and glycemic load (GL) values compared to controls, reinforcing the need for tailored dietary adjustments [64].

In studies examining fructose's effects on PCOS, Johnson et al. found no significant differences in weight loss or metabolic changes between a low-energy fructose-rich diet and a standard low-energy diet. However, further research is required to delineate fructose's specific impact on PCOS-related risk factors [82].

These findings collectively underscore the critical role of carbohydrate quality and quantity in managing PCOS. Dietary strategies emphasizing low-GI, low-carbohydrate, and nutrient-dense foods can significantly alleviate

metabolic and reproductive dysfunctions associated with this condition. Table 1 summarizes some studies about carbohydrates and their influence on PCOS, focusing on the type of carbohydrate.

Impact of fat on PCOS

Fats and oils both provide lipids, which include fats and oils. Aside from being an excellent source of energy, fats also aid in cell growth, fetal brain development, bodily activities, and the utilization of fat-soluble vitamins (A, D, E, and K) [89]. Lipids primarily consist of glycerol and fatty acids. They might be classified as either saturated or unsaturated fatty acids. Saturated fatty acids, including animal lipids, solidify when left at room temperature. Consuming saturated fats raises the risk of cardiovascular disease [90]. Those that include unsaturated fatty acids remain liquid even when left out of the fridge. Vegetable oils, including sunflower, maize, soybean, canola, and olive oils, include these types of fats, which may be either monounsaturated or polyunsaturated [91]. Mechanisms connecting fat to metabolic and reproductive problems. Obesity, affected by both low and high birth weights, is a significant contributor to insulin resistance, dyslipidemia, and hyperinsulinemia, all of which are elements of metabolic syndrome. These factors substantially increase the risk of cardiovascular illnesses and lead to systemic metabolic disturbances [92]. Moreover, modified leptin release from adipose tissue, characteristic of obesity, results in leptin resistance and diminished leptin sensitivity, further disrupting hypothalamic-pituitary regulation. This imbalance induces luteinizing hormone (LH) hypersecretion and hyperandrogenism, impairing ovarian function and resulting in monthly abnormalities, anovulation, and infertility [93]. The feedback mechanisms associated with leptin resistance and hyperinsulinemia intensify hormonal imbalances, obstructing follicle maturation and oocyte development [94]. These interwoven networks highlight the reciprocal relationship between obesity, endocrine dysfunction, and reproductive health, underscoring the necessity for focused therapies to alleviate these impacts. Figure 4 summarizes the association between obesity and PCOS.

Among the macronutrients in the diet, fat is the most calorie-dense, supplying 9 kilocalories per gram, whereas carbs and protein only provide 4 kilocalories per gram. In addition, the human body possesses a nearly boundless capacity to amass fat, particularly in those with hyperinsulinemia. Experiments on overfeeding with fat demonstrate that an abundance of fat decreases the oxidation of carbs without any discernible alteration in fat oxidation. The overabundance of carbs or inadequate carbohydrate oxidation results in an elevation of fat accumulation via the de novo lipogenesis pathway [95]. Cross-sectional research studies have demonstrated a correlation between heightened fat intake and diminished insulin sensitivity. Nevertheless, it is crucial to acknowledge that this correlation is driven mainly by obesity [96, 97]. However, intervention studies have shown that a moderate increase in overall fat consumption (from 20 to 40%) did not significantly impact insulin sensitivity [96]. Therefore, any argument about how high-protein, low-carb diets increase fat intake may be moot, especially regarding short-term interventions [98].

Consuming unsaturated fatty acids has been shown to enhance insulin sensitivity in people with type 2 diabetes or obesity and in healthy people [99, 100]. Nevertheless, people who ingested 5–37% of their total calorie intake as fat demonstrated the beneficial effects of high-quality fat on insulin sensitivity [100]. Researchers Kasim-Karakas et al. [101] examined the impact of

Table 1 Studies about carbohydrates and their influence on PCOS, focusing on the type of carbohydrate, the model used (animal/human)

Study Title	Type of Carbohydrate	Model	Objective	Reference
Low-Carbohydrate Ketogenic Diet in PCOS	Low-carb, ketogenic	Human	Assess metabolic and endocrine effects	[75]
Effect of Carbohydrates on Inflammation in PCOS	High-carb (Western diet)	Human	Analyze the link between diet, insulin resistance, and inflammation	[77]
Low-Carb vs. Low-Fat Diet in PCOS	Low-carb	Human	Compare effects on insulin sensitivity and body composition	[83]
Meta-Analysis of Low-Carb Diet in PCOS	Low-carb diet	Human	Assess BMI, lipid levels, and insulin sensitivity	[76]
Influence of Low-Carb Diet and Metformin on PCOS	Low-carb diet	Human	Evaluate weight loss and conception rate	[79]
Rodent Models for PCOS	Variable carbs	Animal (Rodents)	Review PCOS models in rodents for metabolic risks	[84]
High-Fat Diet Combined with EV in Rats	High-fat, high-carb	Animal	Develop a combined metabolic PCOS model	[85]
Letrozole and High-Fat Diet in PCOS	High-fat, high-carb	Animal	Induce PCOS-IR model with carb influence	[86]
Plasma Carbohydrate Metabolism in PCOS	High-carb	Human	Analyze glucose metabolism and insulin resistance	[87]
Influence of Carbs in Postmenopausal PCOS	High-carb	Human	Study insulin resistance in postmenopausal women	[88]
High-Carb Western Diet and Inflammation	High-carb	Human	Assess impact of carbs on inflammation in PCOS	[77]

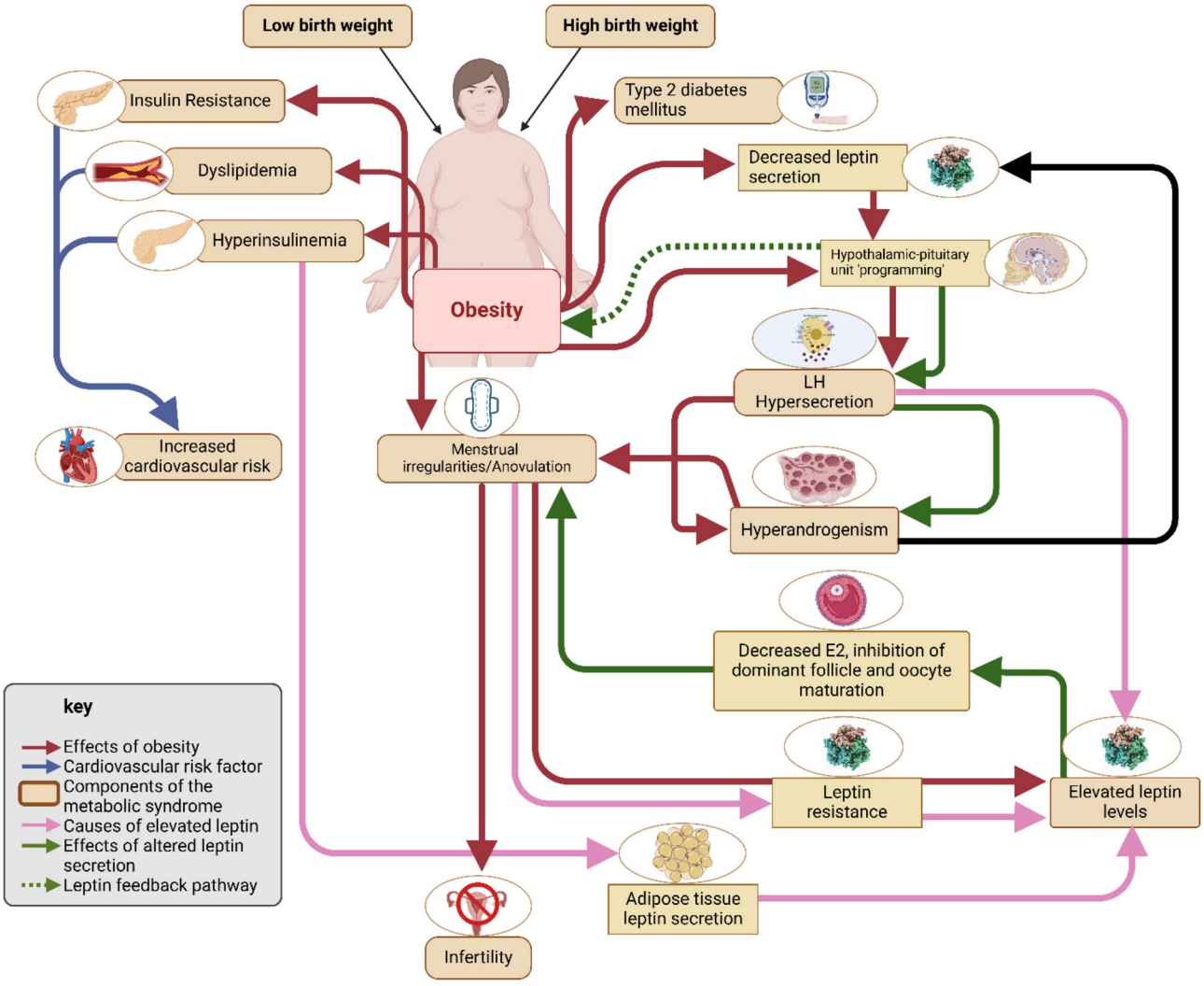

Fig. 4 The relationship between obesity, metabolic dysfunction, and reproductive health is complicated. The table shows the functions of insulin resistance, dyslipidemia, hyperinsulinemia, and altered leptin signaling in the development of cardiovascular risk, menstrual irregularities, hyperandrogenism, and infertility. The most important parts of this process are the influence of leptin feedback, hypothalamic-pituitary dysregulation, and hormonal imbalances on obesity-related outcomes

a diet high in polyunsaturated fatty acids, which have been linked to several health benefits in several other studies. When walnuts were added to diets to raise linoleic and a-linolenic acid levels, there was an unexpected rise in blood glucose levels during fasting and following an oral glucose tolerance test. The levels of reproductive hormones and insulin were unchanged. Long-chain polyunsaturated fatty acids, such as eicosatetraenoic and docosahexaenoic acid, present in fish oil, positively affect metabolic parameters in diabetic patients. However, specific information about their impact on polycystic ovarian syndrome (PCOS) is currently lacking. The benefits of the Mediterranean diet, which is well-known for its high concentration of monounsaturated fatty acids (MUFA), for individuals with PCOS have not been proven, even though it is generally accepted as a standard for healthy eating habits. However, compared to PCOS patients in the United States, a study from Italy revealed a decline in obesity and insulin resistance among PCOS patients [102]. Generally, fat in the diet should not make up more than 30% of total calories, and 10% of those calories should not originate from saturated fat. Spreads and cooking oils are examples of unsaturated fats that should harmoniously mix into the residual fat content. Consuming trans fats and unsaturated lipids with double bonds that exhibit internal resonance has been associated in recent studies with a higher risk of ovulatory infertility [103]. Diets that are low in fat or low in carbohydrates typically lead to a more significant proportion of calorie intake coming from protein. macronutrients and micronutrients, metabolic syndrome, insulin resistance, reproductive health, endocrine disorders.

A recent study indicates that consuming more protein can improve the body's glucose and insulin responses when consuming glucose. However, there is some disagreement on this matter [104, 105]. A higher protein diet can help decrease belly fat by increasing satiety and possibly increasing energy expenditure after meals. Staining lean body mass and promoting muscular growth in response to exercise depend on consuming enough protein. The finding that high blood iron levels are associated with an increased risk of type 2 diabetes has raised concerns regarding overindulgence in red meat [106]. An often-recommended recommendation is for protein to account for 20% of total calories in the diet. To improve this ratio, it may be necessary to reduce the intake of other food components in temporary diet plans intended to help the patient lose weight or improve their glucose tolerance. A key marker of a person's long-term risk for cardiovascular problems is how they metabolize fat if they have PCOS. Typically, this manifests as reduced levels of HDL cholesterol. However, a comprehensive lipid profile that indicates a high risk of developing atherosclerosis is usually not apparent due to relatively low levels of triglycerides. However, even slight variations, such as alterations in the dimensions of lipoprotein particles and an elevation in LDL II and IV subtypes, could potentially contribute to an increased susceptibility to macrovascular disease in people [107].

Combination oral contraceptives containing the antiandrogenic progestogens cyproterone acetate and ethinyl estradiol are commonly recommended to control the menstrual cycle, alleviate excessive androgen-related symptoms, manage endometriosis, and prevent conception. However, the intricate consequences of this substance for glucose tolerance and lipid profiles are still unclear, and the subject is under discussion. It can be seen that in some cases, the conditions may be worsened, and there will be the circulation of increased triglyceride levels [108]. The use of contraceptives may lead to a rise in body weight, and that may endanger the heart's health over time [109]. Statin drugs can help prevent the digestion of unsaturated fats from the mouth. Such medicines aid in decreasing low-grade inflammation that comes with PCOS, a condition where C-reactive protein levels are high [110]. Recently published data points out that statins may induce beneficial effects on the endocrine profile in PCOS, for instance, the lowering of the circulating testosterone level [111]. Lower levels of the blood protein called sex hormone-binding globulin (SHBG) are advised to indicate the anomalous cholesterol measurements which are connected to inhibited insulin signaling, for instance, PCOS [112]. However, the shifting in the figures will likely put a cap on how this method could be used daily in medical activities [113].

Impact of protein on PCOS

PCOS is a common disorder of the endocrine system that usually occurs in women of reproductive age and is often associated with obesity, insulin resistance, and hormonal imbalances. Studies have proven that a protein-rich diet can, to some extent, be beneficial for PCOS management [114, 115]. Diets with higher protein should be based on more excellent fat, less meal weight, and a better metabolism effect from sugar than the ones with carbohydrates [114]. For example, a study discovered that a reduced kcal diet completed with an increase in protein is a practical addition to a reduction in body weight, fat mass, and cholesterol levels, compared to that of another diet without protein but with a supplement of simple sugars [116]. A different survey stated that the high-protein diet resulted in women with PCOS improved glucose metabolism and weight loss even without caloric restriction [117]. Moreover, whey protein administration for one week may influence insulin reaction, which, in turn, can lead to the balance of glucose in the body [118]. Inflammation triggers, including IL-6 and TNF-α, can be alternately found in too high levels due to plant protein intake in overweight and obese adolescent girls with PCOS, which represents possible skin anti-inflammatory capacity [119]. However, these findings are promising, but the relationship between protein intake and hormonal balance with fertility still needs to be answered. A whey protein supplementation short-term research showed no significant alterations in sex hormone-binding globulin (SHBG) or free testosterone levels, which suggests that its effect on fertility might be powerless or restricted [120]. Additionally, glycine, proline, and methionine are types of amino acids that have been blamed for causing PCOS, which gives us a clue to specific dietary choices, the most important being looking at the protein source. Overall, the pattern of a high-protein diet in a moderate and balanced diet seems to favor fat loss, insulin control, and metabolic progress in PCOS. Nevertheless, more detailed investigations are the requirement that must be met to make clear how hormones and pregnancy are affected by this protein level.

Impact of dietary fiber on PCOS

PCOS is a multifactorial endocrine disorder that pertains to reproductive-aged women and is usually linked to insulin resistance (IR), obesity, and hormonal imbalances. Dietary fiber is now recognized as an essential component in managing these metabolic and reproductive problems as it can increase insulin sensitivity, glycemic control, and the balance of hormones. Bridging the knowledge gap between dietary fiber consumption and PCOS outcomes will guide the implementation of nutritional solutions [121]. According to research, too little consumption of dietary fiber brings out a rise in insulin

sensitivity in PCOS women. Cutler et al. (2019) noticed that women with PCOS who resorted to less consumption of dietary fiber had more HOMA-IR scores, fasting insulin levels, as well as raised triglycerides [122]. Alternatively, it was supplemented with high cholesterol HDL levels and improves the body's sensitivity to insulin. On the other hand, the analysis has shown that women with PCOS eat less dietary fiber than controls do. A pooling of 13 studies led to a standardized mean difference (SMD) of -0.32 ($p < 0.001$) in daily fiber intake of PCOS patients compared to controls, which underlines this in difficulties across different geographical regions [123]. The data presented here highlights the fundamental significance of fiber, which plays a primary preventive role in PCOS. Dietary fiber is also recognized as directly affecting hormonal balance in PCOS. Often hyperinsulinemia, which is exaggerated by high levels of androgens, is considered a main characteristic of PCOS. Fiber-rich diets can result in less hyperinsulinemia, and in that way, androgen production will be lesser. Biro et al. (2022) also stated that females with higher fiber consumption had markedly higher testosterone levels; thus, they further confirmed that the hormonal effects are directly related to fiber intake [124]. From the other standpoint, dietary fiber is also a substantial part of dieting; one that might be categorically responsible for want of success in PCO syndrome reaction to such cases. The intake is better fiber, which can make a person full for a long time; moreover, it can cancel blood sugar level fluctuations, which minimizes caloric requirement. Adapting new lifestyle choices may also bear fruit when supporting weight loss efforts. According to Lim et al. (2019), eating low-glycemic, fiber-rich foods was found to be very effective in quitting weight over a period, which then the successful long-term areas were the maintenance of PCOS-related obesity and metabolic dysfunction [125]. In a study conducted by Wang et al. (2022), which included only women suffering from PCOS, it was discovered that the high intake of fiber had a notable impact on the increase of the hormone and the increase in the number of eggs. The mechanism for this was related mainly to the effect of fiber on gut microbiota, which tends to regulate the hormones and fight against inflammation [126]. A low glycemic index (GI) diet, which is often high in dietary fiber, has given women with PCOS a chance to have stable blood sugar and ovulatory issues. It is a fact that these diets have very slow digestion and absorption of carbohydrates, so they lead to a very low glycemic response. Douglas et al. (2006) stated that after the use of low-GI, high-fiber diets for certain periods with PCOS, the women had their menstrual periods at the schedule, and their blood sugar was less than the women who had high-GI diet [81]. Yet another essential factor comes into the picture, along with the power of fiber on lipid metabolism. Soluble fiber has recently appeared to be an outstanding cholesterol (LDL) and triglyceride reducer. Weickert and Pfeiffer (2008) found that soluble fiber improves postprandial glucose metabolism and insulin sensitivity. Therefore these are necessary elements in treating the dyslipidemia that comes with this disease [127]. In many cases, the consumption of micronutrients is paralleled with the intake of dietary fiber, and their joint conduct on PCOS has been the subject of intensive studies. Moran et al. (2013) reported that fiber and magnesium intake was associated with beneficial metabolic parameters in women with PCOS, thus affirming the composite effects of a fiber-rich, nutrient-wise diet lesser the chances of PCOS [128]. Fiber's potential to shift glycemic load (GL) is also important in PCOS treatment. Jeanes and Reeves (2017) also mentioned that most women with PCOS tend to eat food with higher GLs, whereas they intake a small amount of fiber, which leads to lower insulin sensitivity and increased levels of inflammatory markers [129]. Moreover, the team recommended increasing fiber intake against the adverse effects of the lowest GL level and increasing the overall dietary quality [129]. Pulses-based dietary plans, which include legumes and lentils, are another nice option providing fiber in the diet that is good for women with PCOS [130]. The low glycemic load in these diets and the fiber and protein bulk help to reduce after-meal high sugar levels. The study by Kazemi et al. (2018) then provided some substantiation of the fact that the low glycemic index diet, based on pulses, can lead to the improvement of fasting insulin and the decrease of inflammatory markers in case women who have PCOS take it [130]. Support from population studies has added to the evidence on the significance of fiber in controlling metabolic conditions. For instance, Faghfoori et al. (2017) discovered that diets containing a lot of fiber decrease the risks of metabolic syndrome, an often-seen condition in PCOS, especially in advancing insulin sensitivity and lowering systemic inflammation. This is within the confines of the conventional thought that fiber is important to the metabolic health of the organism. A meta-analysis by Ghavami et al. (2023) backed up the lipid-lowering effects of fiber. The study observed that the 5–10 g/day increase of soluble fiber that was accompanied by a 5–6% decrease in LDL cholesterol was a significant change for PCOS women who, due to their conditioned lifestyle, are at risk of cardiovascular complications like having the heart arteries clogged and impaired blood flow to the heart muscles [131]. Dietary fiber is the most important component of nutritional therapies for PCOS. Benefits start from a drop in insulin resistance and androgen levels, go on to help lose weight, and are completed by improvements in glycemic and lipid profiles. These data reveal the necessity for dietetic recommendations of higher fiber intake in women with PCOS. Future research is needed to

customize fiber-based interventions for the various displays of this multifactorial disease.

Micronutrients

This section corresponds to vitamins and minerals necessary for the human body to work in micro amounts. Dietary modifications play a crucial role in managing the clinical features of PCOS. As illustrated in Fig. 5.

Vitamins and minerals

Vitamins help in the body's various chemical processes. Often, humans cannot synthesize some of their vitamins and must obtain them via food. We need this number of vitamins for optimal health: 13. Vitamins are classified into two groups: those water-soluble (like vitamin C and the B-Complex) and those fat-soluble (like vitamins A, D, E, and K) [91]. The body cannot make minerals, so they must be eaten. The body needs to consume some essential minerals (for example, iron, potassium, and calcium) in relatively large quantities to ensure the body can function correctly. Conversely, minute amounts of essential minerals such as zinc, selenium, or copper are recommended to make life prosper [132].

The connection between PCOS and vitamin and mineral consumption

PCOS is a multifactorial endocrine disorder affected by genetic, metabolic, and lifestyle factors. A novel discussion topic has been the link between polycystic ovarian syndrome and the absorption of vitamins and minerals. Certain nutrients have been found to be activators of important metabolic pathways involved in PCOS, such as insulin resistance hyperlipidemia, oxidative stress, and inflammation, thus providing some possible medical means for treating the condition [65]. The results of a recent Mendelian randomization study have drawn attention to the fact that there is a causal relationship between the plasma levels of vitamins A, D, E, K, and B12 and the reduced risks associated with PCOS. If a person had a deficiency of these vitamins, they were more likely to develop insulin resistance, hyperlipidemia, and obesity which are key pathways involved in the pathophysiology of PCOS [133]. More than that, it has also been

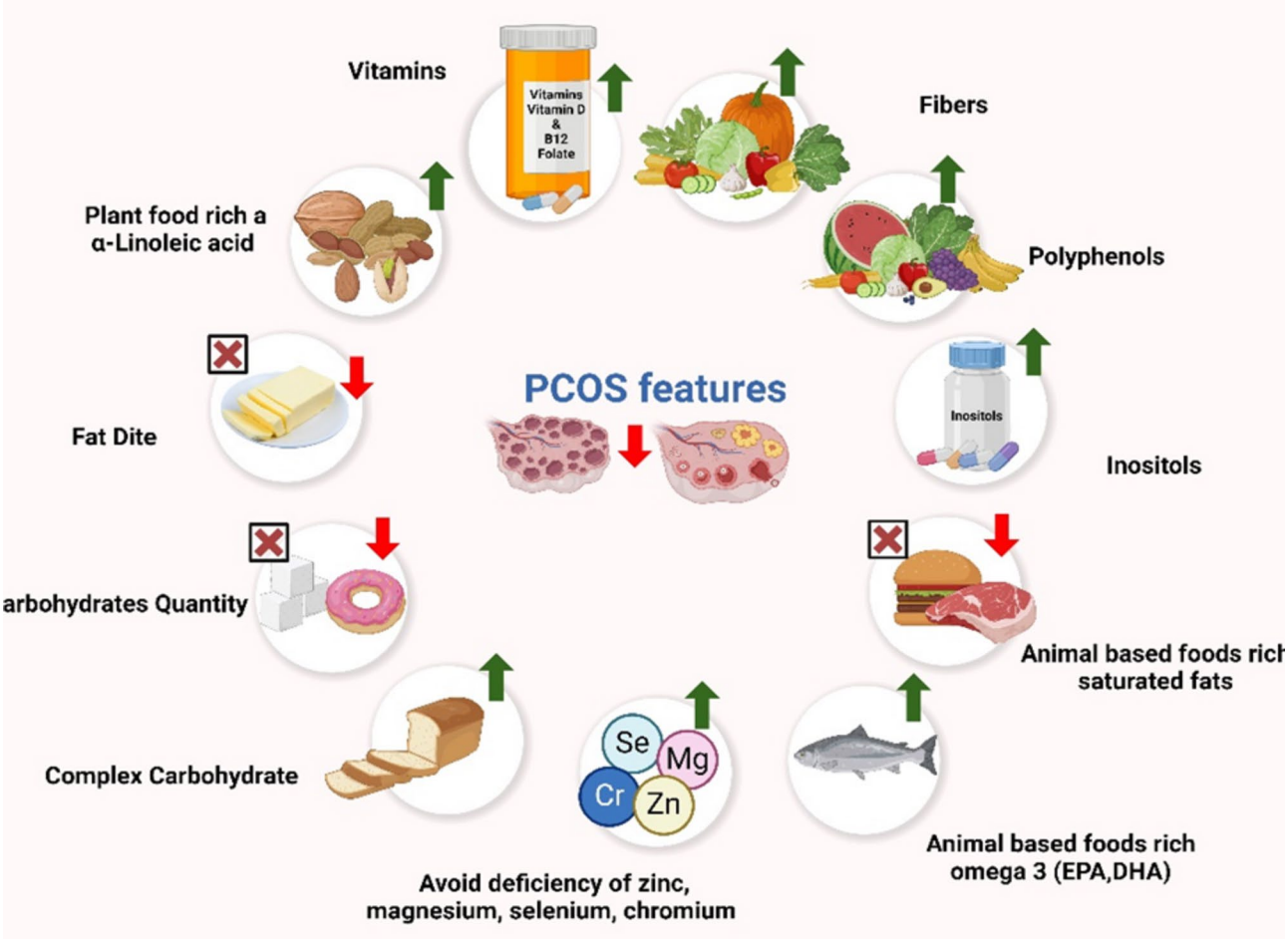

Fig. 5 Macronutrients and micronutrients that may help in PCOS

evidenced that vitamin E alone significantly diminishes the risk of PCOS, and other associated conditions, such as hyperlipidemia and insulin resistance. This is in line with the fact that E vitamin fortification promotes the synthesis of good lipids, lowers insulin levels, and helps to counteract the harmful oxidation process in PCOS [134] . Vitamin D, an essential nutrient, has yielded varying results in treating polycystic ovarian syndrome (PCOS). Although some surveys found a negative relationship [missing], [fulfill], Mendelian analyses contradicted that D-vitamin [referent] has only a weak relevance with lipid levels in connection with less weight gain and insulin resistance in women experiencing PCOS problems [135]. The variations in findings clearly prove the necessity for more clinical and mechanistic studies that can explain vitamin D's role in managing PCOS [136]. Vitamin B12, the essential substance on which energy is transformed, and homocysteine levels are regulated, was also found to be the most important in managing PCOS. The association of increased B12 levels with a lower risk of PCOS and obesity has shown the potential of this vitamin in the moderation of metabolic and inflammatory pathways. Nevertheless, its influence on insulin resistance needs further examination, not excluding its benefits. Vitamin K, on the other hand, has indicated the ability to relieve oxidant stress and to enhance the patient's glycemic control that is affected by PCOS, in spite of the necessity for the in-depth studies necessary for the validation of these findings [133]. Vitamin A, well recognized for its importance in immune system functions and cell differentiation, could be a beneficial factor for preventing hyperlipidemia in PCOS. However, its close relation with PCOS, obesity, and insulin resistance was not statistically significant, which suggests that its effects could be more related to certain metabolic parameters instead of being globally beneficial in the clinical manifestation of PCOS [133]. The study emphasizes the intricacy of vitamin supplementation in PCOS, which is responsive to the treatment based on the synergy between genetic predispositions, dietary intake, and metabolic status. Whilst it has been found that the problems of PCOS and its key pathways are lessened because of the higher levels of vitamins A, D, E, K, and B12, appropriate supplementation techniques are still not fully established for various PCOS phenotypes. The diversity in the responses of individuals is the main reason for this. These discoveries highlight the need for nutritional programs designed for each case and scientific studies to clarify whether vitamins and minerals are important in PCOS treatment . In conclusion, the intersection between PCOS and vitamin and mineral intake signals the chance of nutritional management in this multi-disciplinary medicinal diagnosis. Direct usage of vitamins of Classes A, D, E, K, and B12 may be a useful path to correcting metabolic and hormonal imbalances in PCOS; however, the need for further research is still present to implement them at the location of clinical practice. Chromium picolinate (CrP) is a compound that contains 12.4% elemental trivalent chromium (Cr3+), an essential mineral found in many whole grains, fruits, lean meats, and vegetables. According to studies, supplementation of CrP may be the direction of treating insulin resistance, glycemic control, and metabolic status in women with PCOS [137]. Some RCTS and meta-analyses have been performed, and the results have shown that CrP is effective in some cases; for instance, studies indicated that hirsutism, acne, and TAC were significantly decreased, and TAC was improved after 8 weeks of a daily intake of 200 μg [138]. Moreover, reports are inconsistent, indicating that BMIs, fasting insulin, and free testosterone levels decreased in some meta-analyses, but in other studies, there were no substantial changes in BMI or insulin resistance; however, the testosterone increase was recorded in total and free form. Based on these contradicting findings, one would conclude that the observation of CrP supplementation's potential influence on PCOS in women is conflicting; thus, the demand for additional information is pronounced for reaching convincing conclusions concerning its efficacy. Furthermore, calcium, a vital mineral, has been put forward as an effective means to treat PCOS [139]. Multiple studies have identified abnormalities in calcium concentrations among women with PCOS, often attributed to deviations in vitamin D and parathyroid hormone levels [140]. Research suggests that calcium deficiency may be a common concern for women with PCOS, although the exact relationship between calcium status and insulin resistance remains uncertain [141]. Since vitamin D enhances calcium absorption, supplementation with calcium and vitamin D has been investigated for potential benefits. In women with PCOS who have vitamin D deficiencies, co-supplementation of calcium and vitamin D has demonstrated improvements in β-cell function, TAC, high-sensitivity C-reactive protein (hs-CRP), and glutathione (GSH) levels [142]. Some RCTs have also reported beneficial effects of combining vitamin D with magnesium, zinc, vitamin K, and vitamin E, showing improvements in hormonal balance, inflammation, and oxidative stress. A systematic review of six RCTs involving 480 participants found that calcium and vitamin D co-supplementation significantly improved lipid profiles, menstrual regularity, follicular maturation, insulin resistance, fasting blood glucose, and testosterone levels. These findings suggest that calcium and vitamin D act synergistically to regulate reproductive and metabolic systems, ultimately benefiting women with PCOS [143].

Magnesium is a crucial intracellular cation cofactor for numerous enzymes involved in insulin metabolism [144]. Hypomagnesemia has been linked to impaired insulin

action and the development of insulin resistance due to reduced tyrosine-kinase activity at the insulin receptor level. Magnesium is also involved in the DNA and RNA synthesis that safeguards the death of neurons from cells. The relationship between vitamin D and calcium status and newly diagnosed SCAD has not yet been established. In abstract form, vitamin D and calcium levels are not usually measured during acute myocardial infarction. Thus, vitamins were not prescribed to such patients; it is unknown if they had a deficiency. These findings suggest that increasing serum levels of vitamin D would be, in principle, beneficial [145]. A systematic review of epidemiological studies in women with PCOS indicated a relationship between higher insulin sensitivity and lower magnesium status [145]. However, findings from RCTs have been inconsistent, with some studies showing improvements in insulin resistance and others failing to demonstrate significant effects. Women with PCOS may be more prone to magnesium deficiency and inadequate dietary intake, warranting further research to explore the role of magnesium supplementation in improving insulin resistance and psychological symptoms in this population. Selenium is an essential trace element that is a key component of selenoproteins, which play a crucial role in redox processes, antioxidant defense, and anti-inflammatory functions [146]. Selenoproteins guard against oxidative stress primarily by constraining reactive oxygen species (ROS) and reactive nitrogen species (RNS) [147]. The susceptibility of products to destruction by oxidants is critical, and so is selenium, which emerged as a key factor in embryonic testis formation and general fertility [148]. Women with PCOS tend to have lower plasma selenium concentrations, potentially contributing to free radical accumulation and hyperandrogenism. A systematic review of five RCTs found that supplementation with 200 μg of selenium daily for 8 to 12 weeks reduced insulin resistance, inflammation, and oxidative stress [149]. However, the effects on BMI, fasting blood glucose, lipid profiles, hormonal levels, and PCOS-related symptoms such as acne and hirsutism were inconsistent. While selenium supplementation appears to hold promise for improving metabolic and inflammatory markers in PCOS, further studies are needed to determine its overall efficacy and optimal dosage [150]. Zinc is another essential trace element involved in over 300 enzymatic functions, including insulin synthesis, storage, secretion, and signaling [151]. It has been described as an insulin-mimetic, as it stimulates lipogenesis and glucose uptake in adipocytes through mechanisms like insulin. Zinc's regulatory actions on protein tyrosine phosphatase activity in insulin-like growth factor-1 (IGF-1) signaling pathways suggest its potential role in mitigating insulin resistance [152]. Deficiencies in zinc have been observed in some women with PCOS, and it has been hypothesized that this may contribute to the insulin-resistant phenotype of the condition. A systematic review analyzing zinc supplementation in PCOS found that doses ranging from 4 to 50 mg daily for 8 to 12 weeks resulted in improvements in insulin resistance (HOMA-IR) and lipid profiles while also reducing inflammatory markers such as hs-CRP and oxidative stress markers like malondialdehyde (MDA) and TAC [153]. Some trials also reported reductions in free testosterone, follicle-stimulating hormone (FSH), and dehydroepiandrosterone sulfate (DHEAS) levels, suggesting a potential hormonal benefit [154]. However, many of these studies involved co-supplementation with other nutrients such as magnesium, calcium, and vitamin D, making it difficult to isolate the specific effects of zinc alone. Table 2 summarizes the connection between PCOS and vitamin and mineral consumption.

The treatment of polycystic ovarian syndrome with diet

Dietary treatment for PCOS has become a cornerstone of managing the condition, addressing the metabolic and hormonal imbalances that are hallmarks of the disorder. Lifestyle interventions, particularly dietary modifications, are widely recommended as first-line treatments to improve symptoms and enhance the overall quality of life in women with PCOS [160]. Various dietary approaches, including low-carbohydrate, ketogenic, Mediterranean, and low-glycemic index (GI), target specific metabolic pathways to alleviate the effects of the condition, as shown in Fig. 6. The Mediterranean diet has been given a great reputation worldwide because of its anti-inflammatory qualities. It mostly consists of consuming fruits, vegetables, whole grains, nuts (i.e., almonds, hazelnuts, walnuts, pistachios), and healthy fats (i.e., olive oil/olive, sunflower oil). This dietary approach has significantly shown a reduction in insulin resistance, an improvement in menstrual regularity, and an increase in fertility among women with PCOS. The Mediterranean diet, including a low-carbohydrate diet, has been found to have a connection with a decrease in inflammation, normalization of insulin sensitivity, and good cholesteric outcomes in women with polycystic ovary syndrome [161]. Different dietary patterns depend on individual nutritional strategies, which are also effective for treating PCOS. For example, the vegan diet, which relies heavily on pulses for protein needs, requires 175 ml/day, serving as a fiber and nutrient quality provider. The low-glycemic index diets are about whole foods that healthfully raise blood sugar balances. These have a macronutrient split of 50% carbohydrates, 30% fats, and 20% proteins; this is supposed to be a way to cure diabetes and lower the rate of glycemic spikes with insulin [162]. The DASH diet (Dietary Approaches to Stop Hypertension) is a balanced method of taking high blood pressure medicines with fewer

Table 2 Summary of the connection between PCOS and vitamin and mineral consumption

Nutrient	Effect on PCOS and Related Pathways	Pathways/Outcomes	References
Vitamin E	Reduces insulin resistance and hyperlipidemia; significant antioxidant effects	Insulin resistance, hyperlipidemia	[133]
Vitamin B12	Decreases PCOS and obesity risks; linked with improved metabolism of homocysteine	PCOS, obesity	[133]
Vitamin D	Suggestively linked to reduced hyperlipidemia; inconsistent evidence on PCOS and insulin resistance improvement	Hyperlipidemia	[133]
Vitamin A	Associated with decreased hyperlipidemia risk; limited effect on PCOS and insulin resistance	Hyperlipidemia	[133]
Vitamin K	Reduces obesity risk; potential role in improving glycemic control and alleviating oxidative stress	Obesity	[133]
Chromium Picolinate	Improves insulin resistance, glycemic control, and metabolic status; reduces hirsutism and acne	Enhances insulin signaling, reduces fasting insulin and BMI (mixed results on testosterone levels)	[155]
Calcium	Involved in vitamin D metabolism, may improve insulin sensitivity and hormonal regulation	Regulates β-cell function, TAC, hs-CRP, and GSH levels; supports follicular maturation	[156]
Magnesium	Supports insulin metabolism, neuronal function, and DNA/RNA synthesis; possible role in IR and depression	Improves insulin resistance (inconsistent evidence), potential effects on mental health	[157]
Selenium	Antioxidant and anti-inflammatory properties protect against oxidative stress, potential role in reproductive health	Reduces insulin resistance, inflammation, and oxidative stress; mixed results on BMI and hormonal parameters	[158]
Zinc	Insulin-mimetic effects supports insulin synthesis, secretion, and function; role in metabolic and hormonal regulation	Improves HOMA-IR, and lipid profiles, reduces oxidative stress, inflammatory markers, and androgen levels	[159]

adverse side effects. The diet consists of 1600 kcal/day with 20–30% fats, 50–55% carbohydrates, and 15–20% protein, while sodium intake is less than 2.4 g/day [163]. Ketogenic diets, characterized by a very low carbohydrate and high fat intake, are structured at approximately 1672 kcal/day, with macronutrient ratios of 4.8% carbohydrates, 71.1% fats, and 24.1% proteins, promoting weight loss and metabolic improvements through ketosis [164]. The Mediterranean diet, with an intake of 2222 kcal/day, includes a balanced macronutrient profile of 37% fats, 18% proteins, and 18% carbohydrates, emphasizing high fiber, olive oil, vegetables, and fish for cardiovascular and anti-inflammatory benefits [165]. Low-carbohydrate and ketogenic diets are particularly effective in addressing hyperinsulinemia and weight gain, both critical factors in PCOS management. Ketogenic diets have been shown to reduce body weight, improve insulin sensitivity, and lower androgen levels, which can alleviate symptoms such as hirsutism and acne [166]. Moran and colleagues performed a systematic review that brought to the fore these diets' capability to promote weight loss and reproductive health [122]. It is noted that low-GI diets play a significant role in weight loss, ovulatory function improvements, menstruation regularity, and fertility rates in PCOS women, which is why low-GI diets are considered among the effective ways of stabilizing blood sugar and minimizing insulin spikes in nadir- and zenith-states. It has been noted that low-GI diets are successful in bringing about ovulatory regulation, improving menstrual regularity, and increasing the fertility of women with PCOS. The research studies have revealed that women who observe a dietary plan that is low in GI will have a greater chance to actually ovulate regularly and reduce insulin resistance among those who are on mainstream diets [133]. The role of micronutrients in the dietary management of PCOS is vital. It has been shown that common deficiencies in vitamin D, inositol, and omega-3 fatty acids, which are linked to poor metabolic and reproductive outcomes, are widespread. Researchers have found that insulin sensitivity, menstrual regularity, and fertilization can be improved by providing these nutrients. Specifically, by taking extra vitamin D, insulin metabolism and ovulatory function benefit, and it thus becomes the most important aspect of managing PCOS [167]. The consumption of fewer calories, in addition to sufficient protein intake, has proved to be another effective approach to treating PCOS symptoms. A hypocaloric diet is aimed at the weight recovery of patients, which is a main factor that can lower their insulin resistance and androgen levels. A research study showed that calorie restriction, when coupled with a high-protein diet, resulted in a better metabolic and reproductive rate compared to the common diets [168]. The effectiveness of dietary interventions is increased in the case of regular physical activity and changes in behavioral routines. The endocrinological benefits of dietary changes are reinforced by exercise when this increases insulin sensitivity, reduces visceral fat, and is a major determinant in the

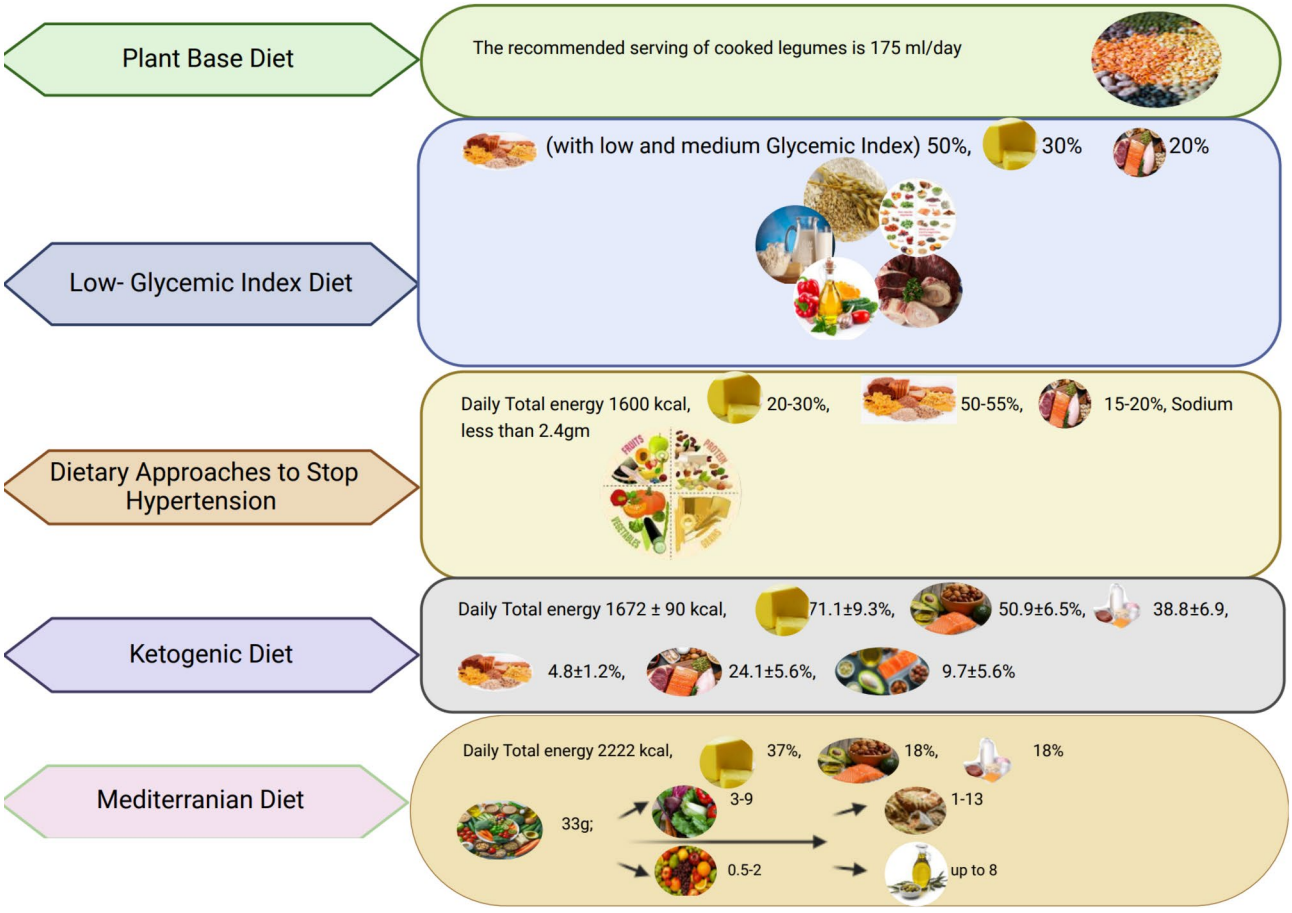

Fig. 6 Overall composition and distinguishing features of food habits

individual's overall well-being. The duty of dietary food packages and organized exercise workouts in not only fat loss but also health improvement are the main culprits of body composition transforming, menstrual cycle regularizing, and deteriorating lifestyle in PCOS females [169]. Although there have been encouraging results, it is difficult to figure out the perfect diet for PCOS treatment due to the disorder itself being heterogeneous. It is important that every person has his diet planned according to their metabolic and reproductive needs. To ensure that the PCOS has the proper diet, they need more research in order to utilize real data to the fullest [170]. To sum up, diet modifications act as a core element for women who are managing Polycystic Ovary Syndrome by tackling all the metabolic, hormonal, and reproductive disorders. Regardless of low-GI, ketogenic, Mediterranean, or plant-based diets, promoting a balance of nutrients in diet and weight control, as well as the substitution of certain vitamins and minerals, make sure women diagnosed with PCOS get a complete plan to benefit from an improved prognosis. As more research comes forth, individualized dietary methods are considered the ultimate solution for the health and procreational issues faced by those with this intricate syndrome. Several studies have assessed the effects of various dietary interventions on the clinical outcomes of women with PCOS. As summarized in Table 3.

Other supplements and PCOS

Various dietary supplements, including probiotics, melatonin, N-acetyl cysteine (NAC), resveratrol, Coenzyme Q10 (CoQ10), and omega-3 fatty acids, have shown potential to improve insulin sensitivity, hormonal balance, inflammation, and reduce oxidative stress in women with PCOS. These supplements play a crucial role in metabolic and reproductive health, as shown in Fig. 7. Probiotics have shown promising results in PCOS management. Studies indicate probiotic supplementation can improve insulin sensitivity, lipid profiles, and inflammation markers. A meta-analysis demonstrated that probiotics significantly decreased fasting blood insulin levels, triglycerides, and very low-density lipoprotein cholesterol while improving insulin sensitivity in women with PCOS [176]. Another study found that probiotics helped regulate sex hormone-binding globulin (SHBG), reduce testosterone levels, and lower markers of oxidative stress

Table 3 Reviewed studies assessing the effect of different dietary compositions on PCOS

Group	Food system	Key findings	Reference
50 obese and PCOS women group	– 23 women followed a traditional diet – 27 women who followed a calorie diet.	- Reduced body weight - Reduces insulin levels - Improved lipid profile - Having enlarged ovaries -Increased insulin sensitivity	[171]
Group of 60 overweight or obese women	Traditional low-calorie diet and modified low-calorie diet	- reduce body weight - Lowers testosterone levels -Lowering LDL - Decreases insulin levels	[172]
26 individuals were diagnosed with PCOS	Low glycemic diet with the same calorie intake	- reduced body weight - Increased insulin sensitivity -Development of non-steroidal fatty acids	[173]
48 individuals diagnosed with PCOS	DASH diet	- reduce body weight - Low triglyceride levels - Reduced VLDL - Increased insulin sensitivity -Development of non-steroidal fatty acids	[174]
60 individuals diagnosed with PCOS	Low-calorie diet	-BMI decreased -hirsutism score decreased -Reduced waist circumference	[175]

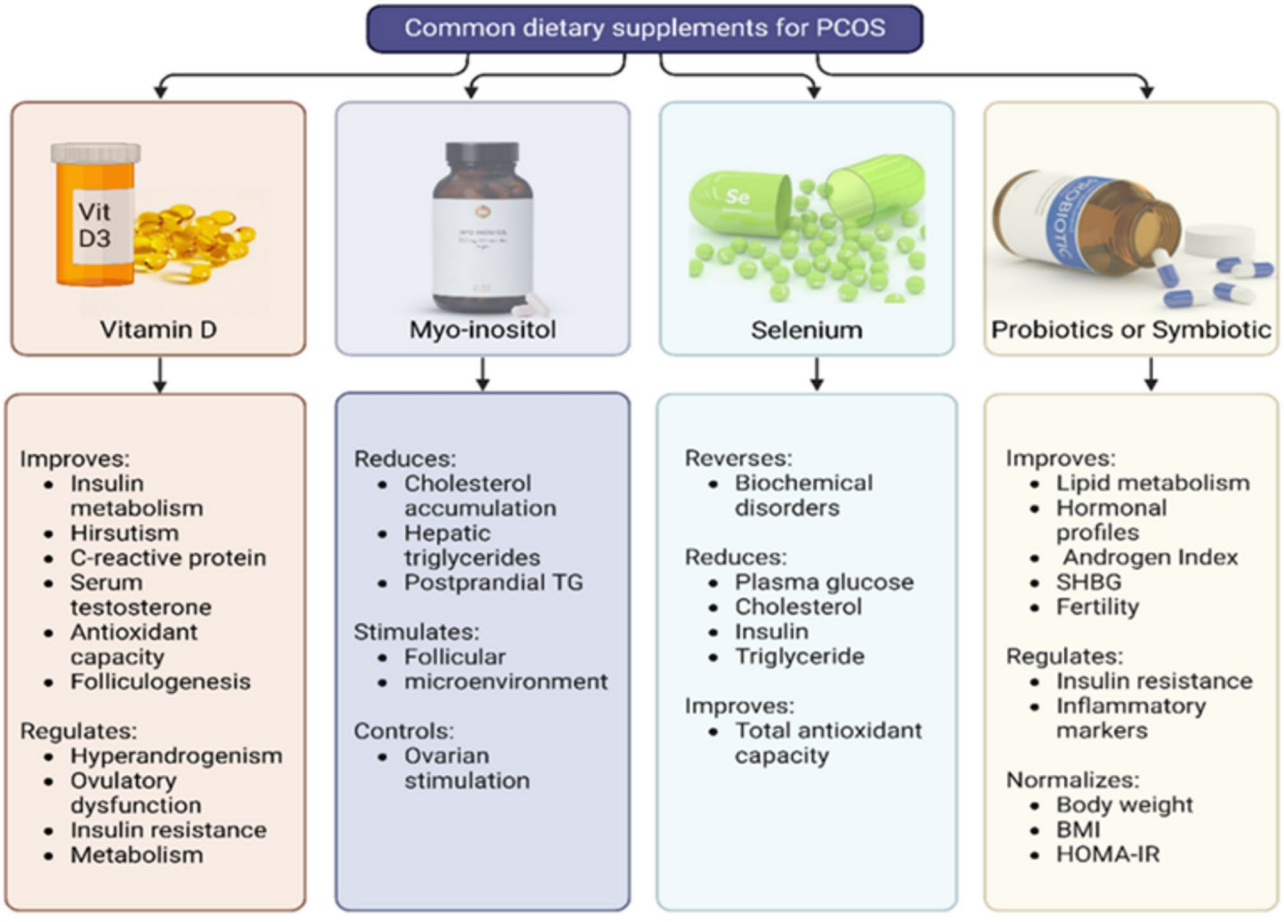

Fig. 7 Overview of common dietary supplements used in the management of Polycystic Ovary Syndrome (PCOS), highlighting their specific benefits and roles in improving metabolic, hormonal, and reproductive health parameters

[52]. Cozzolino et al. (2019) performed a meta-analysis encompassing 13 studies involving 855 participants with PCOS ($n = 438$ interventions and 417 controls), revealing significant increases in SHBG (SMD: 0.56; 95% CI: 0.26, 0.86) and NO (SMD: 0.38; 95% CI: 0.09, 0.68) concentrations. Conversely, the free androgen index (SMD: − 0.58; 95% CI: 0.95, − 0.21) and MDA (SMD: − 0.76; 95% CI: 1.46, − 0.05) concentrations exhibited significant reductions in the probiotics and symbiotic groups compared to placebo [177]. Other hormonal and inflammatory markers, including testosterone, DHEAS, GSH, hs-CRP, TAC, and hirsutism scores, exhibited no significant differences between the group's macronutrients and micronutrients, metabolic syndrome, insulin resistance, reproductive health, endocrine disorders [178].

Interventions were frequently administered for 12 weeks, and the strains commonly included Lactobacillus acidophilus/casei/rhamnosus, Bifidobacterium bifidum/longum/breve, and Streptococcus thermophilus, with nearly all randomized controlled trials incorporating Lactobacillus acidophilus in their probiotics [179]. A further meta-analysis included data from six randomized controlled trials involving 406 women with polycystic ovary syndrome (aged 25 to 28.5 years) who received probiotic supplements for 8 to 12 weeks [176]. Probiotic supplements reduced fasting insulin, QUICKI, triglycerides, and VLDL, but did not affect other metabolic parameters, including fasting blood glucose, HOMA-IR, additional lipids, body weight, hs-CRP, or DHEAS. All randomized controlled trials incorporated Lactobacillus acidophilus, Lactobacillus casei, and Bifidobacterium species, and the aggregated results remained statistically significant following the leave-one-out sensitivity analysis [180]. Melatonin may be pertinent in PCOS as it is believed to directly diminish testosterone production through its anti-gonadal effects, alongside its advantageous roles in alleviating insulin resistance, hyperglycemia, and dyslipidemia [181]. A systematic analysis identified three research (two randomized controlled trials and one cell culture study) involving women with polycystic ovary syndrome getting therapy with assisted reproductive technologies [182]. A meta-analysis of all three studies, which included both in vivo and ex vivo melatonin administration, demonstrated a significant impact of melatonin treatment on clinical pregnancy rates (in vivo studies utilized 3 mg of melatonin from the onset of the first cycle or day 3 until the triggering day; the ex vivo study employed 10 μmol/L of melatonin in the culture medium for 24–48 h) [183]. However, this significance was not observed in the meta-analysis of the two randomized controlled trials (RCTs) conducted exclusively in vivo. Two more prospective studies involving women with PCOS indicated that melatonin administration of 2–3 mg/d for 2–6 months resulted in a reduction of androgens, LH, anti-Müllerian hormone, and BMI while increasing FSH levels [184, 185]. Jamilian et al. (2019) performed a randomized controlled trial involving 56 women with PCOS, revealing a decrease in hirsutism, total testosterone, hs-CRP, and MDA, alongside an increase in TAC and total GSH among participants administered 5 g of melatonin twice daily for 12 weeks, in contrast to the placebo group [186]. The researchers have also experimented with melatonin to see if it can be useful in PCOS treatment. It comes out that if melatonin has a positive effect on granulosa cells, it decreases androgen production and enhances heme oxygenase-1 expression, which gives a direct reflection of the benefits for oocyte quality and also helps in oxidative stress issues [187]. Furthermore, the contribution of melatonin in relation to modulating the symptoms of PCOS through its involvement with the regulation of appetite and metabolic processes highlights the importance of this part of treatment [188]. N-acetyl cysteine (NAC) is an impressive substitute for PCOS with another potential way [189]. It has been evidenced that antioxidative, apoptosis and Ca + + flux can be muffled via transient receptor potential vanilloid 1(TRPV1) channel in the neutrophils of PCOS patients, where the potential role might be the anti-inflammatory turnouts and the improvement of the insulin resistance [190]. A different study also showed that NAC could significantly enhance the lipid profile, hormonal equilibrium, and ovulation status by becoming a more effective alternative to other insulin-lowering medications [191]. In PCOS studies, the impact of taking NAC on insulin receptor function and insulin release in response to glucose was investigated. From what research has already been suggested, a 2015 meta-analysis of eight randomized controlled trials ($n = 910$) showed that women with PCOS who were treated with 1200–1800 mg/d of N-acetylcysteine (NAC) for 12–24 weeks experienced three times as many pregnancies and live births as those that received the placebos. However, there was a 60% higher conception rate with metformin than with NAC. Moreover, NAC proved to be the most effective option compared to metformin and placebo as it was the only one that significantly decreased fasting blood glucose. At the same time, it did not make any difference in the fasting insulin or HOMA-IR levels [192]. Even though the NAC treatment showed promising results, it is difficult to draw any firm conclusions because of the limited number of studies, the small sizes of the samples, and the overall insufficient quality of the information available. Along with the polyphenol's natural antioxidant and anti-inflammatory activities, resveratrol may be beneficial in treating PCOS by modulating epigenetic pathways and decreasing inflammatory markers. It has also been related to improving metabolic activity and lowering the risk of chronic diseases connected with

PCOS [193]. The role of Coenzyme Q10 (CoQ10) supplementation in treating PCOS to prevent oxidative stress and related metabolic disorders has been analyzed. It has been effective in enhancing insulin sensitivity and lowering indicators of inflammation. Thus, PCOS management can benefit from the intervention [194]. Omega-3 fatty acids are a type of polyunsaturated fat, which includes eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which is said to fight inflammation, and got to mention that it also improves insulin sensitivity. Clinical studies have suggested that omega-3 supplementation has a beneficial effect on various health factors, such as remission of C-reactive protein (CRP) and improvements in lipid profiles, as well as the insulin resistance in PCOS patients has been lessened [195]. A further study showed that omega-3s, combined with probiotics, contributed to a greater extent in the area of metabolic health, such as improved insulin sensitivity and markers of inflammation [196].

Herbal medicine and PCOS

Herbal medicine has recently risen in notice for its possible contribution in treating polycystic ovary syndrome (PCOS), specifically by affecting improvements in metabolic parameters, insulin sensitivity, and hormonal balance [197]. The hypoglycemic effect of the study which took place, cinnamon (Cinnamomum cassia), which includes insulin receptor autophosphorylation and GLUT-4 receptor synthesis, may be -mediated. This study has been carried out [198]. The reports of antibacterial activity by active compounds like eugenol and cinnamaldehyde are not exaggerated [199]. The meta-analysis of Heydarpour et al., which reviewed five high-quality trials involving 448 women with PCOS, showed that cinnamon supplementation decreased fasting blood sugar, fasting insulin, and HOMA-IR [200]. The researchers also noted lipid profile changes, yet no major effects were seen in body weight or BMI. The dosages that researchers used in these studies ranged from 336 mg daily of cinnamon extract to 1500 mg daily in capsule form over 6 to 24 weeks, indicating the need for further investigations to determine the right dosing and duration of therapy. After recognizing the potential benefits of Chinese herbal medicine in PCOS, especially in the areas of insulin resistance, inflammation, and ovarian function, it began to be tested. Certain active compounds, including glucosides and alkaloids, are believed to affect metabolic pathways. A review conducted by Cochrane in 2015, with Ried as the author, analyzed five randomized controlled trials with the participation of 414 participants and found low-quality evidence showing that Chinese herbal medicine combined with clomiphene citrate (CC) would possibly increase pregnancy rates compared to CC alone [201]. However, there was no significant difference when comparing Chinese herbal medicine alone to CC, and no studies reported on live birth rates, indicating a lack of strong evidence to support its effectiveness in treating PCOS-related infertility. Curcumin, the active compound in turmeric (Curcuma longa), has demonstrated hypoglycemic and anti-inflammatory effects through its ability to reduce TNF-α and inhibit oxidative stress markers. In a randomized controlled trial of 67 women, curcumin supplementation (500 mg three times daily for 12 weeks) significantly decreased fasting blood glucose and DHEA levels compared to placebo. However, there was no change in fasting insulin levels [202]. Another study involving 51 women found that curcumin improved insulin sensitivity (QUICKI index) after six weeks of supplementation but did not significantly alter lipid or glycemic markers compared to placebo [203]. The research findings above are indicative of the potential of the drug curcumin on the improvement of glucose metabolism and hormonal balance in the case of PCOS. However, more extensive studies must be conducted to confirm its long-term impact. Sage (Salvia officinalis) is a plant of Iranian origin that is rich in phytochemicals like Rosmarinus acid and flavonoids by this, it can help to control glucose metabolism and insulin sensitivity. According to the result of the research of Amini and his colleagues among 70 euglycemic women with PCOS, who received a sage extract supplementation for eight weeks, it was noted that the participants communicated a decline in BMI and huge gains in the area of insulin resistance and fasting insulin level [204]. It should be concluded that, however, the sage might have metabolic benefits but needs further investigation of its influence on body composition and cardiovascular markers because there are no significant changes observed in the waist-to-hip ratio of the study participants' blood pressure. Fennel (Foeniculum vulgare) is another herb with potential therapeutic effects in PCOS due to its phytoestrogenic properties, which may weakly mimic estrogen and influence metabolic and hormonal regulation [205]. A study conducted by Mokaberinejad et al., a random clinical trial, proved that 55 women compared the efficacy of fennel tea and dry cupping therapy to metformin treatment [206]. Fennel tea, including dry cupping following six menstruations, was determined to be as effective as the widely prescribed medicine - metformin in shortening the menstrual cycle length and bringing down the BMI after the six-month observation of the six months. Based on this, fennel may replace the conventionally administered drug treatments, thereby serving as a healthier alternative. That being the case, it requires larger sample studies to confirm those claims that a combination of spearmint (Mentha spicata), ginger (Zingiber officinale Roscoe), cinnamon, and citrus have also been studied for their anti-inflammatory and hypoglycemic effects in women with PCOS. It is

said menthone, flavonoids, and terpenoids are the agents of this usefulness. A study commissioned by Ainehchi et al. assessed the effects of this herbal concoction in synergy with the clomiphene citrate (CC) as well as the herbal concoction alone in the sixty women who failed the test [207]. After three menstrual cycles, the women who took the herbal mixture with or without the use of CC exhibited a substantial improvement in serum antioxidant concentrations, insulin resistance (HOMA-IR), fasting blood glucose, and insulin levels in relation to the group that used CC only. However, no significant differences were found in menstrual regularity among the groups, suggesting that while this herbal blend may support metabolic health, its effects on reproductive function remain unclear. Overall, while herbal medicine presents promising avenues for managing PCOS-related metabolic and hormonal imbalances, the existing evidence remains mixed. Many studies highlight potential benefits in improving insulin sensitivity, glucose metabolism, and lipid profiles, but inconsistencies in dosing, study duration, and methodology limit definitive conclusions. Further well-designed, large-scale clinical trials are necessary to establish standardized recommendations for herbal treatments in PCOS.

Conclusions and future perspectives

The study revealed the impact of nutrition on polycystic ovary syndrome, with a case of PCOS emphasizing the importance of a diet rich in fruits, whole grains, and vegetables and low in carbohydrates, cholesterol, and saturated fats, highlighting the significant impact of a nutrient diet in the prevention and management of PCOS. Insulin resistance related to obesity and PCOS. Women with both PCOS and obesity exhibit high levels of insulin resistance. The roles of macronutrients and micronutrients in managing PCOS are addressed, focusing on the potential benefits of vitamin and mineral supplementation. There is a case for using dietary regimens; most of the investigated diets are effectively improved, increased insulin sensitivity, and reduced body weight and insulin levels, while waist circumference is reduced during intake of the Low-calorie diet, which is essential in women's treatment with PCOS. However, dietary intake patterns and lifestyles are essential markers in the case of PCOS. Further investigations have a crucial role in better understanding and improving PCOS management.

This study has several limitations despite offering a comprehensive review of nutritional and herbal approaches to managing PCOS. First, the current body of evidence lacks large-scale, long-term randomized controlled trials (RCTs) evaluating the sustained effects of specific diets and herbal supplements in diverse populations. Many studies reviewed are observational or based on small sample sizes, which limits generalizability. Additionally, dosage, formulation, and duration variations of herbal interventions make it difficult to standardize therapeutic recommendations.

There is also limited research on individualized dietary strategies tailored to specific PCOS phenotypes (e.g., lean vs. obese PCOS), which may respond differently to macronutrient composition or supplementation. Furthermore, heterogeneity in diagnostic criteria across studies makes it challenging to compare outcomes consistently.

Future research should focus on:

- Conducting well-powered RCTs with standardized protocols to evaluate efficacy and safety.
- Exploring personalized nutrition strategies based on metabolic profiling.
- Investigating the synergistic effects of combined dietary and herbal interventions.
- Assessing the long-term impact of these interventions on fertility outcomes, quality of life, and metabolic health.
- Including adolescent and perimenopausal populations to broaden the scope of applicability.

Abbreviations

PCOS	Polycystic Ovary Syndrome
IR	Insulin Resistance
BMI	Body Mass Index
LH	Luteinizing Hormone
FSH	Follicle-Stimulating Hormone
AMH	Anti-Müllerian Hormone
GnRH	Gonadotropin-Releasing Hormone
HG	Hyperinsulinemia
ACTH	Adrenocorticotropic Hormone
DHEA	Dehydroepiandrosterone
DHEAS	Dehydroepiandrosterone Sulfate
HOMA-IR	Homeostatic Model Assessment of Insulin Resistance
HDL	High-Density Lipoprotein
LDL	Low-Density Lipoprotein
VLDL	Very Low-Density Lipoprotein
TAC	Total Antioxidant Capacity
GSH	Glutathione
MDA	Malondialdehyde
SHBG	Sex Hormone-Binding Globulin
hs-CRP	High-Sensitivity C-Reactive Protein
TRPV1	Transient Receptor Potential Vanilloid 1
EPA	Eicosapentaenoic Acid
DHA	Docosahexaenoic Acid
CoQ10	Coenzyme Q10
NAC	N-Acetyl Cysteine
CrP	Chromium Picolinate
RCT	Randomized Controlled Trial
CC	Clomiphene Citrate
LCKD	Low-Carbohydrate Ketogenic Diet
GL	Glycemic Load
GI	Glycemic Index
PP	Premature Pubarche
SCAD	Stable Coronary Artery Disease

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