

Polycystic Ovary Syndrome (PCOS) -Associated Infertility: Clinical Insights and Emerging Deep Learning Approaches for Early Detection and Prediction

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Abstract

Polycystic ovary syndrome (PCOS) is the most common endocrine-metabolic disorder in women of reproductive age and a major cause of anovulatory infertility around the world. It is a heterogeneous disorder characterised by chronic oligo- or anovulation, clinical and/or biochemical hyperandrogenism, and polycystic ovarian morphology, often complicated by insulin resistance and obesity. This review highlights current understanding of the epidemiology, pathophysiology, diagnostic criteria, mechanisms of infertility due to PCOS, and management of PCOS patients. Due to significant inter-observer variability in ultrasonography assessment of the polycystic ovarian morphology, more and more research work is being done in using deep learning (DL) algorithms such as convolutional neural networks (CNN) and DL-based architecture including InceptionV3, ResNet, VGG16, and DenseNet to automatically diagnose the polycystic ovarian morphology and predict PCOS risk from clinical and hormonal data. In this review we discuss DL architectures used in studies, the datasets, their performances, and limitations, and future directions of using artificial intelligence in infertility in PCOS.

Keywords: Polycystic Ovary Syndrome (PCOS), Female Infertility, Deep Learning, Ovarian Ultrasound, Artificial Intelligence.

I. INTRODUCTION

a) What is Polycystic Ovary Syndrome (PCOS)?

Polycystic Ovary Syndrome (PCOS) is one of the most common endocrine disorders affecting women of reproductive age worldwide. It is a heterogeneous condition characterized by reproductive, hormonal, metabolic, and psychological manifestations. The prevalence of PCOS varies according to the population studied and the diagnostic criteria applied, with estimates commonly ranging between 8% and 13% [1], [2]. The condition is characterized by features including ovulatory dysfunction, clinical or biochemical hyperandrogenism, and polycystic ovarian morphology.

Elevated androgen levels may be associated with clinical manifestations such as acne, hirsutism, and androgen-related scalp hair loss. In addition to reproductive and hormonal abnormalities, PCOS is associated with metabolic disturbances, including insulin resistance, obesity, impaired glucose tolerance, and an increased risk of type 2 diabetes and cardiovascular risk factors [1], [3]. The heterogeneous nature of PCOS results in substantial variation in clinical presentation and disease severity among affected individuals [27].

PCOS is commonly diagnosed using the Rotterdam-based diagnostic framework. In adults, the diagnosis is generally established when two of three features are present after exclusion of other relevant conditions: (i) ovulatory dysfunction, (ii) clinical and/or biochemical hyperandrogenism, and (iii) polycystic ovarian morphology on ultrasound [1], [2]. The 2023 International Evidence-Based Guideline further provides updated recommendations for the assessment and management of PCOS and emphasizes an individualized approach to diagnosis and treatment [1].

Although these diagnostic criteria provide a standardized framework, the diagnosis of PCOS can be challenging because of the heterogeneous presentation of the disorder. Some women may exhibit polycystic ovarian morphology without the complete clinical syndrome, whereas others may demonstrate hyperandrogenism and ovulatory dysfunction without characteristic polycystic ovarian morphology [1], [27]. Therefore, accurate diagnosis requires integration of clinical, biochemical, and imaging findings together with appropriate exclusion of alternative endocrine disorders.

b) Difficulties in Conventional PCOS Diagnosis

The diagnosis of PCOS traditionally relies on clinical history, physical examination, biochemical investigations, and ovarian ultrasound. Although these methods remain fundamental to clinical practice, their interpretation may be influenced by differences in clinical expertise, laboratory methods, imaging quality, and diagnostic criteria [1], [2]. In particular, ultrasound-based assessment of ovarian morphology and follicular characteristics may be affected by image quality, equipment, operator experience, and inter-observer variability.

Hormonal investigations also require interpretation within the appropriate clinical context. Clinical manifestations of hyperandrogenism may overlap with those of other endocrine conditions, while biochemical measurements can be influenced by assay methodology and laboratory-specific reference ranges [1]. Consequently, PCOS diagnosis cannot generally be established using a single biomarker or imaging feature and instead requires integration of multiple clinical, biochemical, and morphological characteristics.

Another important limitation is the complexity of the diagnostic pathway. Clinical assessment, laboratory investigations, and ultrasound examination may be required to establish the diagnostic phenotype and exclude alternative causes of reproductive or endocrine abnormalities. These challenges may be more pronounced in settings where access to specialized healthcare professionals, standardized ultrasound equipment, and laboratory testing is limited [26]. Such limitations highlight the need for objective, reproducible, efficient, and automated approaches that can support clinicians in PCOS assessment and clinical decision-making.

c) Contribution of Deep Learning to PCOS Diagnosis

Deep learning has emerged as a promising approach in medical diagnosis because of its ability to automatically learn complex patterns from large and high-dimensional datasets. In medical imaging, convolutional neural networks (CNNs) and related deep learning architectures can extract discriminative features directly from images, reducing the dependence on manually engineered image features. This has generated increasing interest in the application of deep learning to ovarian ultrasound images for PCOS assessment [9]–[13].

Ultrasound is particularly relevant to PCOS assessment because ovarian morphology constitutes one component of the diagnostic framework. Recent studies have investigated automated recognition, classification, segmentation, and feature extraction from ovarian ultrasound images using deep learning techniques. Zhao et al. developed a deep learning-based automatic recognition model for PCOS using ovarian ultrasound images and demonstrated the potential of automated image analysis for PCOS classification [9]. Similarly, recent research has investigated transfer-learning-based CNN models for integrating ultrasound characteristics and biochemical biomarkers for PCOS diagnosis [10].

Several CNN architectures, including ResNet, AlexNet, DenseNet, InceptionV3, and other transfer-learning models, have been investigated for PCOS classification using ovarian ultrasound images [11]–[13]. These approaches can learn image representations associated with ovarian morphology and may assist in reducing the subjectivity and time associated with conventional image interpretation.

Recent developments have also extended beyond direct image classification toward automated segmentation and image enhancement. Reka et al. proposed an automated PCOS detection framework incorporating super-resolution ultrasound images and a Segment Anything Model, demonstrating the potential of combining image enhancement, segmentation, and deep learning-based classification for automated ovarian analysis [28]. Such approaches indicate the growing potential of computer-aided analysis for supporting ultrasound-based PCOS diagnosis.

In addition to image-based approaches, artificial intelligence methods can utilize structured clinical information, including body mass index (BMI), hormonal measurements, metabolic parameters, and patient history. By learning nonlinear relationships among multiple clinical variables, machine learning and deep learning models may assist in identifying individuals at increased risk of PCOS. Furthermore, multimodal learning provides an opportunity to combine ultrasound-derived features with clinical and biochemical information. Such integration may provide a more comprehensive representation of the heterogeneous PCOS phenotype and potentially improve diagnostic performance [10].

d) Purpose and Impact of This Research

Despite the rapid growth of research on artificial intelligence and deep learning for PCOS diagnosis, several challenges remain. Many published studies have been conducted using relatively small, institution-specific, or non-standardized datasets, which may limit the generalizability of their findings to other populations and clinical environments [9]–[13], [28]. Differences in image

acquisition protocols, diagnostic criteria, preprocessing techniques, model architectures, and evaluation metrics also make direct comparison between studies difficult.

Another important challenge concerns the interpretability of deep learning models. Many deep learning systems operate as complex models whose decision-making processes are not readily understandable to clinicians. Limited interpretability may reduce confidence in their use as clinical decision-support tools. In addition, high performance on retrospective datasets does not necessarily demonstrate clinical effectiveness. Independent external validation, prospective evaluation, standardized datasets, and assessment in real-world clinical environments remain important requirements for translation into routine clinical practice [9], [28].

Given these limitations, this review aims to systematically examine existing deep learning-based approaches for PCOS diagnosis and identify important research gaps. Particular attention is given to image-based, clinically informed, and multimodal deep learning approaches. The review also examines commonly used datasets, preprocessing techniques, model architectures, evaluation metrics, and reported performance measures across the existing literature.

The overall objective of this review is to provide an organized overview of current deep learning applications in PCOS diagnosis, with particular emphasis on ultrasound-based approaches and the integration of clinical information. Furthermore, the review discusses methodological and clinical challenges and identifies potential future research directions for developing reliable, interpretable, generalizable, and clinically applicable artificial intelligence-assisted diagnostic systems for PCOS.

II. EPIDEMIOLOGY AND BURDEN OF DISEASE

Polycystic ovarian syndrome affects up to 6-10% of reproductive-age women, but this estimate varies based on different criteria used for diagnosis, from around 6% with the NIH criteria up to 15-20% with Rotterdam criteria [1,5]. In a Global Burden of Disease study conducted across 204 countries/territories, PCOS-associated infertility was shown to contribute significantly to years lived with disability, with the burden concentrated mainly in high-sociodemographic index regions due to improved diagnosis, as well as the impact of obesity and sedentary behaviour as risk factors for PCOS in these regions [5]. The increasing trend in obesity prevalence globally is projected to raise the burden of PCOS-related infertility in the future [3,5].

III. PATHOPHYSIOLOGY OF PCOS-ASSOCIATED INFERTILITY

The pathogenesis of PCOS is considered to be multi-factorial and encompasses the interaction between neuro-endocrine, ovarian and metabolic alterations contributing to folliculogenesis and ovulation failure [1,4,6].

a) Neuro-endocrine Abnormalities

One of the key abnormalities characterizing PCOS is the elevated frequency and intensity of gonadotropin-releasing hormone (GnRH) pulsatility, which stimulates excessive secretion of luteinizing hormone (LH) in comparison with follicle-stimulating hormone (FSH) [4,6]. Excessive LH-to-FSH ratio leads to androgen hypersecretion by the ovaries and adrenals together with the insufficient FSH stimulation for normal follicular maturation, leading to follicular arrest and anovulation [4,6].

b) Hyperandrogenism

High androgen levels, either ovarian or adrenal, interfere with dominant follicle selection and induce an accumulation of small antral follicles in the arrested state of development – the cause of PCOS morphology on ultrasound [1,4]. In addition, high androgen levels are associated with the signs of hirsutism and acne characteristic of PCOS [1].

c) Insulin Resistance and Hyperinsulinaemia

An insulin-resistant state is common among women with PCOS and is independent of body mass index, leading to hyperinsulinaemia [3,6]. High insulin concentrations synergize with elevated levels of luteinizing hormone (LH) to increase the production of androgens by ovaries and also reduce the production of SHBG in the liver [6,7]. Insulin resistance is even more pronounced in the obese condition; in addition, the dysfunction of the liver and adipose tissue has recently become regarded as a factor contributing to and caused by the development of PCOS [3,7].

d) Increased Levels of Anti-Müllerian Hormone (AMH)

PCOS women usually have two to three times higher blood levels of AMH compared to normal women, because of the increased number of small antral follicles [1,4]. High AMH levels are known to inhibit the development of follicles due to its direct inhibitory action on FSH and the enzyme aromatase, and has been identified as an alternative marker to follicle ultrasound counts [1].

e) Chronic Low-Grade Inflammation

Recent research suggests that chronic low-grade inflammation, oxidative stress, and adipokine and hepatokine signalling are key factors involved in the persistence of metabolic and reproductive symptoms in PCOS, indicating that the condition should be regarded as a systemic disorder rather than just an ovarian one [3,7].

IV. DIAGNOSTIC CRITERIA

In accordance with the 2023 International Evidence-Based Guideline for the Assessment and Management of PCOS, the revised Rotterdam criteria have been adapted into evidence-based guidelines [1,2]. In adults, the following two of the three criteria need to be fulfilled in order to establish a diagnosis after ruling out other conditions such as thyroid disorders, hyperprolactinemia, and non-classic congenital adrenal hyperplasia [1]:

- Excess of androgens clinically and/or biochemically
- Ovulatory dysfunction (oligo/anhormone)
- PCOM or increased AMH level in place of ultrasonography

It should be noted that in case of irregular menstrual cycles and presence of clinical hyperandrogenism, there is no need for further ultrasound or AMH measurements [1,2]. Both hyperandrogenism and ovulatory dysfunction need to be present in adolescents, while ultrasonography is not advised due to poor specificity as it is common in this age due to physiological occurrence of multi-follicular ovaries [1].

V. MECHANISMS UNDERLYING THE ASSOCIATION BETWEEN PCOS AND INFERTILITY

Infertility in patients suffering from PCOS is mainly caused by chronic anovulation, yet there are usually other contributing factors [4,23]. Oocytes obtained from PCOS patients, especially in

combination with insulin resistance, display lower capacity for development which may be related to unfavourable hormonal conditions in follicles [6,21]. In addition, endometrium may be poorly receptive because of the prolonged exposure to unopposed estrogen in anovulatory cycles, whereas obesity decreases conception chances and the risk of miscarriages through metabolic and inflammatory pathways [3,6]. All these reasons imply that even ovulation alone does not fully normalize the fertility capacity of women with PCOS [21,23].

VI. MANAGEMENT OF INFERTILITY ASSOCIATED WITH PCOS

a) Lifestyle Change

The most recommended therapy for all women suffering from PCOS and infertility, especially those who have extra body weight, is lifestyle change including diet and exercise [1,3]. Only slight weight reduction (5–10% of total body mass) restores ovulation and increases the efficiency of the subsequent pharmacological treatment by reducing insulin resistance and circulating androgen levels [1,3].

b) Pharmacological Treatment, First Choice: Letrozole

Since the demonstration that letrozole, an aromatase inhibitor, produces higher live-birth rates than clomiphene citrate, with a lower rate of multiple pregnancies due to the shorter half-life and more selective follicular selection, it is now the recommended choice for the preferred pharmacological treatment for ovulation induction among women with PCOS-induced anovulatory infertility [1,8].

c) Pharmacological Treatment, Second Choice

If ovulation induction with letrozole is ineffective in producing pregnancy, other options may be considered, including clomiphene citrate (alone or in combination with metformin), low dose gonadotropin therapy with ultrasound control to minimize multiple pregnancies or laparoscopic ovarian drilling [1,14]. Metformin enhances insulin resistance and regulates the menstrual cycle without providing much improvement in live-births on its own; it is not recommended for use in pregnancy [1,14].

d) Surgical Treatment

Assisted reproductive technology, in particular in vitro fertilization (IVF), potentially coupled with in vitro oocyte maturation, is suggested as third-line therapy in case of failure of ovulation induction and/or existence of another indication for IVF, e.g., tubal or male-factor infertility [1,21]. OHSS must be carefully considered as a complication in case of the typical high antral follicle count in PCOS [1,16].

e) New and Adjunct Therapies

Anti-obesity drugs such as GLP-1 receptor agonists, and bariatric/metabolic surgery is gaining acceptance in obese females with PCOS, based on evidence showing marked improvement in metabolic and reproductive parameters, including ovulatory cycles [3,24]. Myo-Inositol, which serves as an insulin sensitiser, has been included as an adjunct in the updated International PCOS Guideline of 2023 based on results of a systematic review and meta-analysis that shows benefits in terms of metabolic and in some instances, reproductive parameters [15]; a network meta-analysis has also indicated that myo-inositol is more effective compared to metformin in improving IVF/ICSI success rate and reducing the risk of ovarian hyperstimulation syndrome [16,18], but an

umbrella review of all the existing meta-analyses revealed that the evidence base is mainly of low-to-moderate certainty [17,20]. Additional adjuncts that have been studied for PCOS women undergoing IVF include Vitamin D supplementation due to the negative effect of vitamin D deficiency on oocyte and endometrial outcomes [22], and individualized approach to ovarian stimulation protocol (commonly a GnRH-antagonist protocol with an agonist trigger), coupled with optimal BMI and AMH dosing to prevent OHSS [19,21].

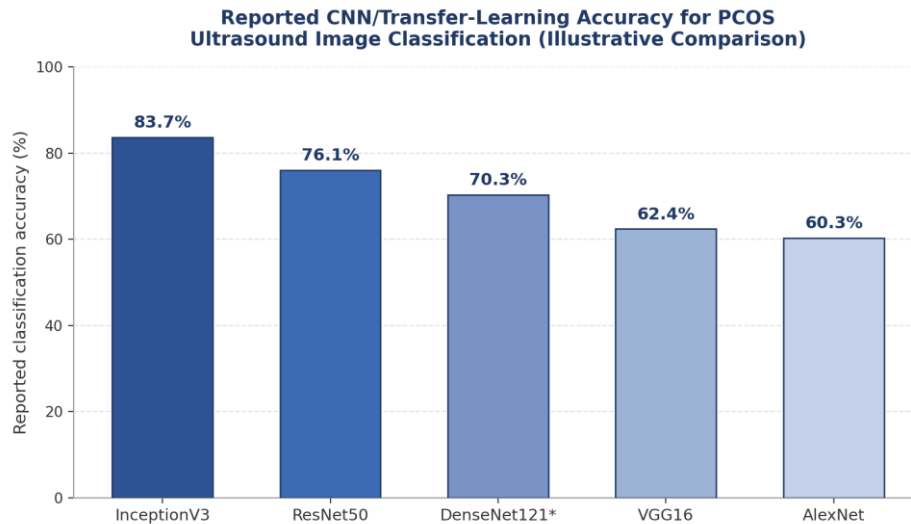
VII. DEEP LEARNING APPROACHES TO PCOS DIAGNOSIS AND FERTILITY PREDICTION

The biggest problem in the conventional approach to the diagnosis of PCOS is that the interpretation of transvaginal ultrasound images for polycystic ovarian morphology is both operator-dependent and subjective along with the complex set of biochemical and clinical criteria [9,13]. Over the recent several years, much research has been done with regard to using deep learning (DL) techniques in order to solve this problem in two main areas of application: (i) diagnosis of PCOS based on the images from ovarian ultrasound, and (ii) prediction of risk based on clinical and hormonal data sets [9,10,11].

a) Convolutional Neural Networks for Ultrasound-Based Diagnosis

The dominant method for automated detection of polycystic ovarian morphology on ultrasound is the convolutional neural networks (CNN) [9,13]. The transfer learning, i.e., fine-tuning of the CNN trained on natural image datasets is very efficient because of the relative scarcity of the PCOS ultrasound datasets [12,13]. Reported CNN architectures include InceptionV3, ResNet18/ResNet50, VGG16, AlexNet, and DenseNet121. All of the above-mentioned CNNs have achieved accuracies of more than 90%, and some even higher than 97-99% in single-center studies in detecting PCOS ovaries [11,13,28]. Also, more recent studies have used object detection frameworks to perform automatic localization and classification of ovarian follicles in ultrasound images to standardize follicle counting and decrease the variation of follicle counting between different observers similar to the process of computer-aided diagnosis in ovarian cancer [9,11].

Performance metrics vary widely based on architecture and type of follicle: While some architectures such as AlexNet and InceptionV3 have performed well in terms of precision in PCOS diagnosis (classification of PCOS ovaries from healthy ovaries), the classification of more specific anatomical structures such as dominant follicle has proved to be more difficult and demonstrates the limitations of the approach of using transfer learning for fine-grained subtypes in the context of ovary images [11,29]. Also, hybrid methods of performing classification tasks which combine feature extraction via CNNs with conventional machine-learning methods such as ensemble or stacking via meta-learners like bagging or boosting have been proposed [12].



*Figure 1 Reported classification accuracies for five widely used CNN/transfer-learning architectures applied to PCOS ultrasound image classification. Values for InceptionV3, ResNet50, VGG16, and AlexNet are drawn from a single comparative study (Reka et al., 2025) evaluating baseline pre-trained classifiers on the same ultrasound dataset prior to the authors' proposed enhancement pipeline. The DenseNet121 value (marked *) is drawn from a separate study evaluating a related but distinct three-class ovarian-condition task and is included for illustrative context rather than direct comparison. Reported accuracies for these architectures vary substantially across the wider literature — from the low 60s to above 99% — depending on dataset size, image quality, class balance, and preprocessing pipeline, underscoring the current lack of standardised benchmarking in this field*

As shown in Figure 1, accuracies for the same architectural design vary significantly among different studies [28,29]. For example, the performance accuracy of InceptionV3 has varied from approximately 84% up to more than 99%, whereas the VGG16 model has been demonstrated an accuracy range between approximately 62% and 91% [10,13,28]. These variations arise due to the actual differences in the size of datasets, image quality, balance of classes, etc., but also show that the accuracy numbers used for specific PCOS deep learning models in each individual paper need to be considered as dataset-specific results instead of architecture properties. This also proves the need, discussed further in the next section, for standardised, multicentre benchmarking datasets allowing comparable analysis of different architectures for PCOS.

b) Multimodal and Biomarker-Based Models

Since PCOS diagnosis requires both imaging and biochemical parameters, there were also multimodal deep learning models incorporating both ultrasound features along with other clinical and hormonal biomarkers such as LH/FSH ratio, AMH, and androgenic hormones [10]. These multimodal integrations, achieved through transfer learning-based multimodal CNN models, showed a higher accuracy of the diagnosis when compared with image- or biomarker-only models [10]. These integrative approaches, exemplified by transfer-learning-enhanced CNN models

combining ultrasound and biomarker data, have reported improved diagnostic accuracy over image-only or biomarker-only models, mirroring similar multimodal strategies developed for ovarian cancer risk stratification (for example, models combining ultrasound with CA-125 levels) [10].

c) Predictive Modelling for PCOS-Related Infertility and Treatment Response

In addition to diagnosis, other aspects of PCOS that may benefit from predictive modelling via machine learning and deep learning include the likelihood of spontaneous or drug-induced ovulation, responses to letrozole or clomiphene treatment, and chance of successful live births with assisted conception via IVF [10,21]. Such models usually depend on structured datasets including anthropometric parameters (BMI), hormone levels, and menstrual cycle traits and use methods like random forest, gradient boosting, or deep neural network analysis; methods such as SMOTE (Synthetic Minority Over-sampling Technique) have been used to solve problems related to class imbalance in clinical training datasets, in particular underrepresentation of rare outcome classes such as non-responses to treatment [10,12].

d) Limitations and Barriers to Clinical Translation

Despite reported high accuracy, existing deep learning approaches to PCOS suffer from a number of key issues. All known models are based on training and validation datasets that are small and single-site; this makes their applicability questionable due to the dependence on specific ultrasound machines, operators, and patients' population [11,28,29]. Class imbalance, inconsistencies in applying diagnostic criteria while labelling the training dataset, and lack of external validation are common problems [12,29]. Similar systematic reviews on ovarian cancer imaging have shown that the vast majority of deep learning models in this related field are primarily developed in order to improve detection accuracy, but do not place enough emphasis on the aspect of model validation and assurance in a broad sense, which is as crucial an issue for PCOS research as well [9,11]. Additionally, it should be noted that deep learning models operate mainly as "black boxes", and the limited possibility to interpret them can negatively impact both clinical trust and regulation. Multicentre prospective validation, standardisation of image acquisition procedures, and explainable-AI methods will most probably be required prior to implementing those tools into practice [9,29].

e) Future Directions

Future research in this field is expected to include the use of federated learning methods that would enable model training on several sites without consolidating sensitive patient data, the use of longitudinal data and multi-omics (genomics, metabolomics and microbiome data) in conjunction with imaging, and the development of explainable-AI methods that would allow clinicians to understand the reasons behind the diagnosis or prediction [9,10]. Validation of such tools in prospective studies would allow for earlier and more consistent PCOS diagnosis, personalized choice of ovulation induction regimen, and accurate prediction of IVF outcome.

VIII. PSYCHOSOCIAL ISSUES

Psychosocial implications of infertility caused by PCOS include high levels of anxiety, depression, problems with body image and poor quality of life of affected women when compared to general

population [26]. Accordingly, comprehensive management of infertility in patients with PCOS must include psychological support and education of patients alongside the medical and reproductive interventions [25,26].

IX. CONCLUSION

PCOS continues to be the most common cause of anovulatory infertility on a global scale due to the interaction of neuroendocrine disruption, hyperandrogenism, insulin resistance, and chronic low grade inflammation [1,4,6]. Management of PCOS based on available evidence takes place within a stepwise algorithm starting with lifestyle changes, followed by use of letrozole as primary medical treatment and IVF in refractory cases [1,8,21]. The diagnosis and prognosis of PCOS and infertility related to it are currently being transformed by deep learning algorithms, which have significant potential in terms of standardizing diagnosis using ultrasound and treatment response prediction [9,10,29]. Continued interdisciplinary collaboration between reproductive endocrinologists, radiologists, and data scientists will be essential to translate these computational advances into improved fertility outcomes for women with PCOS [24,27].

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