RESEARCH PAPER

Automated Blastocyst Grading Using Image Processing Techniques with Quantitative Feature Analysis and Performance Evaluation

Prerana Deshpande [1], Dr. Bali Thorat [2]
[1, 2]Dr. G. Y. Pathrikar College of Computer Science & Information Technology,
MGM University, Chh. Sambhajinagar, India
[1]deshpandeprerana105@gmail.com , [2]bthorat@mgmu.ac.in

Abstract

Objectives: To develop a computerized, image-based embryo grading system that offers a consistent, objective assessment of blastocyst quality, with a particular component of blastocyst i.e. trophectoderm (TE) evaluation**. Method**: The suggested approach makes use of advanced image processing methods, such as feature extraction to examine morphological traits including TE density, TE boundary, and morphological features of TE, and image preprocessing to improve clarity. The focus of this study is to extract trophectoderm, feature of blastocyst and its quality is evaluated by using cell arrangement, density and cohesiveness. **Findings:** The proposed ensemble learning model decreases subjectivity related with manual assessment and improves grading consistency, achieving an overall classification accuracy of 86.67% in embryo grading by enabling objective and semi-quantitative evaluation of the feature trophectoderm. The extracted features accurately represent morphological features that are essential for determining the viability of an embryo. **Novelty**: This research introduces a new, fully automated method for blastocyst's feature i.e. Trophectoderm (TE) grading that combines an ensemble learning classifier with quantitative feature extraction based on image processing. It combines morphological features and edge density for objective evaluation, in contrast to conventional subjective methods. An interpretable, economical process that enhances consistency and repeatability in embryo evaluation is the main contribution.

.**Keywords:** Blastocyst, Inner Cell Mass (ICM), Assisted Reproductive Technology (ART), In-Vitro Fertilization (IVF), Trophectoderm (TE)
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1. Introduction

Since 17.5% of adult couples worldwide experience infertility issues each year, many of them choose IVF treatment in order to achieve a successful pregnancy[1]. Accurate selection of viable embryos is essential for increasing success rates in in vitro fertilization (IVF) under Assisted Reproductive Technology (ART). In conventional embryo grading technique embryologist classify embryos depends on the visual evaluation of blastocyst components such as Inner Cell Mass (ICM), Trophectoderm (TE) and Blastocoel. This technique, however, is subjective and risky, which increases the chances of multiple pregnancies, failure of IVF cycle, thus reduces implantation success. Blastocyst at day-5 has higher implantation potential compared to other embryo stages because of their optimal morphological characteristics[2]. Medical diagnosis plays an important role in in vitro fertilization (IVF), where accurate grading of day-5 embryo (blastocysts) can significantly improve treatment outcomes [2]. Conventional embryo assessment methods depends on manual observation, which is often subjective and prone to variability [3]. In order to improve the accuracy and consistency of embryo grading beyond human investigation, machine learning (ML) plays an important role in IVF by making it possible to analyze complicated blastocyst images and clinical data to find delicate patterns and embryo grading [4]. In order to achieve pregnancy, an IVF cycle consists of a series of steps that include gamete selection, embryo culture, quality assessment and implantation[5]. ML-based approaches allow for more objective, consistent, and reproducible embryo grading. The importance of machine learning algorithms in medical research, especially, in embryo grading in IVF, has been emphasized by recent publications[6].

Prior studies on healthy day-5 embryo i.e. blastocyst have mostly employed, Artificial Intelligence (AI) techniques, particularly Deep Learning models such as Convolutional Neural Networks (CNNs), Life Whisperer Genetics, time-lapse video-based embryo grading have been widely applied in IVF for automated embryo assessment and selection. These models enable end-to-end learning from blastocyst images, requires a large datasets and high computational resources that increases cost of IVF treatment. On the other hand, classical Machine Learning (ML) approaches such as Support Vector Machines (SVM), Principal Component Analysis (PCA), and Linear Discriminant Analysis (LDA) and RC (Ridge Classification) depends on handcrafted features and offer better interpretability and efficiency. In this study, ML-based approach is adopted, where quantitative Trophectoderm (TE) features such as edge density and morphological characteristics are extracted using image processing techniques. This approach provides a cost-effective, transparent, and reproducible alternative to both manual grading and data-intensive deep learning models.

By using machine learning algorithms, like ensemble learning classifier, to identify grading of blastocyst images using one feature of blastocyst i.e. Trophectoderm (TE), this work seeks to close this research gap. This research also highlights the potential of machine learning technologies to improve embryo grading and success rate of pregnancy. The objective of this project is to enhance rate of successful pregnancy using machine learning in IVF.

Most of the existing research on automated blastocyst grading concentrates on the combined assessment of several embryo features, such as the Blastocoel expansion, Trophectoderm (TE), and Inner Cell Mass (ICM)[7]. However, despite its important role in implantation potential and embryo viability, our research focuses on independent evaluation of Trophectoderm grading to develop a simplified, objective and efficient framework for automated embryo assessment. In order to create a straightforward, impartial and computationally effective paradigm for automated embryo assessment, the current study particularly concentrates on TE grading. The suggested method look for lower model complexity while preserving dependable grading performance by focusing on a single important feature.

Figure 1 shows microscopic image of day-5 embryo i.e. blastocyst.

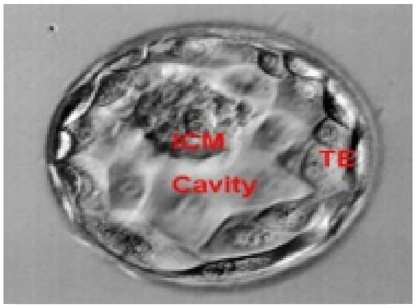


Fig. 1 Microscopic image of Blastocyst

In this research, Gardner's Grading System is used to evaluate Day-5 embryos also known as blastocysts, to determine their developmental quality and convenience for transfer of embryo[7]. The Gardner system grades the blastocyst based on three morphological components: the Blastocoel cavity, the Trophectoderm (TE), and the Inner Cell Mass (ICM)[7]. Each of these features provides essential developmental information. The Blastocoel reflects the degree of expansion of the blastocyst. The Trophectoderm, which later forms the placenta, indicates how well the embryo may support implantation and nourishment. The Inner Cell Mass (ICM) is responsible for forming into the fetus. Better ICM quality is strongly correlated with successful fetal development[4]. Additionally, the Zona Pellucida (ZP) plays a significant role in embryo hatching, which is required before implantation can occur.

To improve objectivity in embryo evaluation, this study applies image processing techniques to extract the feature of blastocyst i.e. trophectoderm and calculate its statistical parameters[4] for further evaluation. Automating part of the grading process reduces human subjectivity, enhances consistency, objectivity and supports embryologists in selecting the most viable embryos. Finally, this technological approach has the possibility to improve implantation outcomes and increase the overall success of IVF treatments. This approach makes Assisted Reproductive Technology (ART) more effective, dependable and accessible for patients. A blastocyst's outermost layer of cells is called the trophectoderm. During pregnancy, it develops into the placenta and other supportive tissues that helps in the embryo's implantation and nutrition. In this research we use the Gardner's Grading System to grade trophectoderm as A (excellent), B (good), or C (poor) [8]. In Gradner's grading system, trophectoderm (TE) is the outer layer of the blastocyst and identified on the basis of the arrangement, quantity and level of cellular cohesion that forms outer layer of the blastocyst. Table 1 shows Gradner's grading system for trophectoderm.

TE grade	Trophectoderm quality
A	Many cells, forming a cohesive layer
B	Few cells forming a loose epithelium
C	Very few large cells

Table 1. TE grade according to Gradner's Grading System

These grades are based on how compact the cells are, how they look, and how many cells are present. Traditionally, embryologists assign the grades by directly observing the embryo under a microscope. This method is subjective and occasionally uneven since it mainly dependent on their own experience and judgment [8].

The goal of this study is to develop an automated approach that uses image processing techniques to identify and grade the trophectoderm. This aids in selecting the ideal blastocyst to implant into the women's womb[8]. Earlier, embryologists classified blastocysts merely by evaluating their morphological appearance using Gardner's grading approach and also called as conventional morphological assessment (CMA). Since this strategy depends totally on human judgment, it can lead to blunders. These errors can lower the success rate of a successful pregnancy or may even lead to problems like multiple pregnancies.

This work uses image processing techniques to extract the trophectoderm and compute its statistical parameters in order to increase objectivity in embryo evaluation[9]. Automating part of the grading procedure improves consistency, lessens human subjectivity and helps embryologists to choose the most viable embryos. This technical approach can improve implantation outcomes and increase the success rate of IVF treatments. It also makes Assisted Reproductive Technology (ART) more effective, reliable, and accessible for patients.

The trophectoderm (TE) is one of the most significant elements of a blastocyst since it later grows into the placenta. As a result, the trophectoderm 's quality plays an important role in determining an embryo's viability. In Gardner's grading system, the trophectoderm is scored as A (excellent), B (good), or C (poor)[8]. The number of cells, position and cohesiveness (compactness) of trophectoderm cells are used to grade them. Traditionally, embryologists assign these grades by directly observing embryo under a microscope. This method is subjective and occasionally uneven since it mainly dependent on their own experience and judgment.

The goal of this study is to develop an automated approach that uses image processing techniques to identify and grade the trophectoderm. This aids in selecting the ideal blastocyst to implant into the womb of the woman [8]. Earlier, embryologists classified blastocysts only by evaluating their appearance using Gardner's grading approach. Since this method depends totally on human judgment, it can lead to blunders. These mistakes may reduce the chances of a successful pregnancy or possibly cause problems like multiple pregnancies.

The suggested approach makes use of an automatic trophectoderm grading system for blastocyst in order to address these problems. After identifying the trophectoderm, the technique computes key characteristics such as its density and edges. These features are produced using diverse image processing approaches including morphological operations, Otsu's thresholding and canny edge detection [10]. The algorithm automatically assigns a grade to the trophectoderm (TE), after extracting these values and comparing them with Gardner's grading requirements. This automated approach lowers human subjectivity, boosts accuracy and helps embryologists make better decisions. In the end, it could lead to better IVF results and more dependable embryo selection.

Naiya Amin et al. used a multifactorial strategy that combines preimplantation genetic testing (PGT), time-lapse imaging (TLI), proteomic and metabolomic profiling, AI-based analysis and conventional morphological grading (Gardner's method). The findings show that combining these techniques lowers the need for invasive treatments like embryo biopsy while increasing the accuracy of embryo selection, improving implantation potential and raising the likelihood of a healthy pregnancy [10]. The study uses a thorough review methodology with an emphasis on artificial intelligence (AI) applications in in vitro fertilization (IVF), including methods like deep learning, transfer learning, and data-driven models used for ovarian stimulation, pregnancy prediction, embryo grading, and clinical decision-making. The results demonstrate how AI has the potential to significantly improve IVF in a number of ways, including accuracy, efficiency, and predictive capability. But issues like data accessibility, model interpretability and moral difficulty still exist.

Lazaros Moysis et al. employed artificial intelligence (AI) applications in in vitro fertilization (IVF); it also including methods like deep learning, transfer learning and data-driven models used for ovarian stimulation, pregnancy prediction, embryo grading and clinical decision-making. The results demonstrate how AI has the potential to improve IVF in a number of ways, including accuracy, efficiency and predictive capability. But it has issues like data accessibility, model interpretability. Considering all conditions and parameters, AI has predicted how to transform viable embryo in in vitro fertilization (IVF) by making it more accurate, dependable and patient-specific treatment plans possible [11].

Mohamed Abouhawwash used Automated embryo quality prediction system, that is much enhanced by combining temporal and morphological information, according to recent study in Assisted Reproductive Technology (ART). With macro F1-scores ranging from 0.356 to 0.479, conventional models without feature engineering or appropriate management of missing data exhibited excellent performance. On the other hand, sophisticated frameworks that use machine learning classifiers like XGBoost, SMOTE-based augmentation and label imputation have made significant progress, integrated techniques have reported weighted F1-scores of 0.902 and macro F1-scores of 0.844, with accuracies as high as 90.1%. Furthermore, the biological significance of important predictive traits has been verified using explainability methods such as SHAP. These results demonstrate how temporal analysis, data balance and imputation techniques can be combined to create embryo selection systems that are more robust, accurate and clinically dependable [12].

According to Hong Ji et al. in assisted reproductive technology (ART), embryo selection has historically been based on morphological grading systems, which are arbitrary and sensitive to change. According to them, the prediction of blastocyst development, can be improved by combining advanced machine learning models like random forest, support vector machines (SVM) and deep learning with statistical models like logistic regression. Also they claimed that the embryo viability is greatly influenced by important variables such mother age, embryo quality. Although the majority of models rely on later-stage or image-based data, this study shown strong prediction ability (AUC > 0.90) [13].

2 Methodology :

2.1.Proposed Method :

Applying Image Processing techniques to the dataset for grading blastocyst i.e. day-5 embryo and find the objective and automated grading system for TE. Fig. 2 shows the proposed automatically grading system.

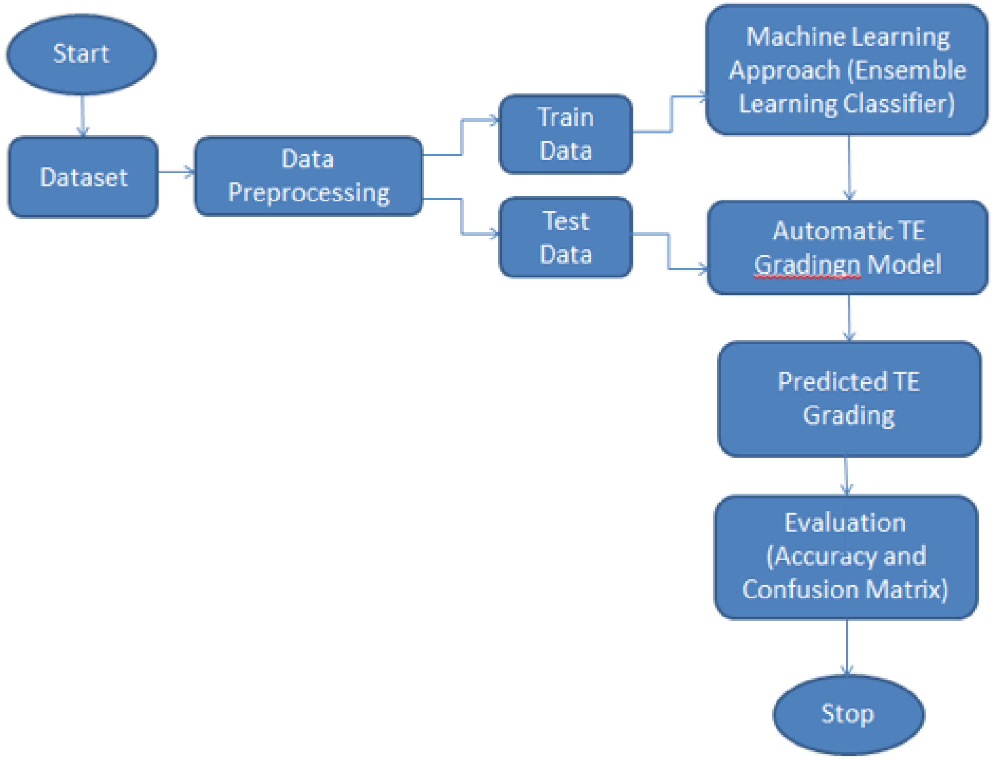


Fig 2. Proposed Method of automated TE grading system

2.1 Data Collection :

The blastocyst day-5 embryo images used in this study were obtained from the publicly available Kaggle Human Blastocyst Dataset for IVF.

Dataset URL: https://www.kaggle.com/datasets/iamshahzaibkhan/human-blastocyst-dataset-for-ivf?select=Gardner_test_gold_onlyGardnerScores.csv. Total 50 images of blastocyst is used for this research. The blastocyst images were stored in the Portabel Network Graphic (PNG) format, with a 384 x 512 pixel (height x width) dimensional resolution. Although the images are stored in RGB color format (8 bits per channel), the images are appropriately grayscale. Roughly 200 to 300 KB are the file sizes of each image. The bright-field microscopy was used to take these images. The dataset was divided into training and testing sets using a 70:30 ratio, where 70% of images were used for training and 30% were used for testing the classification model.

2.2 Image Acquisition and Standardization

Through the dataset of blastocyst images were first loaded and normalized. All RGB images were transformed to grayscale because Trophectoderm (TE) analysis relies more on structural boundaries rather than color. Intensity differences are essential for identifying cell borders and textures are preserved in this process. Furthermore, it lowers the dimensionality of the data, which lowers computing complexity. Grayscale images thus provide a reliable and effective input for further edge identification and analysis.

2.3 Contrast Enhancement using CLAHE

Contrast Limited Adaptive Histogram Equalization (CLAHE) was used to improve the clarity of delicate characteristics like the borders of Trophectoderm cells and to increase the local contrast of blastocyst image. In contrast to global histogram equalization, Contrast Limited Adaptive Histogram Equalization enhances fine details by redistributing pixel intensities within small image sections, or tiles. A contrast limiting (clip limit) technique limits the height of the histogram prior to redistribution in order to avoid over-amplification of noise. In order to prevent false borders, bilinear interpolation is then used to gently integrate the processed tiles. This method improves the accuracy of following segmentation and edge phases while significantly enhancing edge details.

2.4 Noise Reduction using Median Filtering

A median filter with a (5x5) kernel was applied to the contrast-enhanced image in order to decrease noise. Impulsive noise are successfully eliminated by using this technique. It smoothes the image while maintaining critical edge features, in contrast to linear filters. This helps in preserving distinct Trophectoderm borders for precise TE grading.

2.5 Embryo Region Masking

The embryo was divided using morphological techniques and thresholding to assure that TE analysis is restricted to the pertinent area. By filling in gaps and eliminating tiny blemishes, the binary image was improved. The blastocyst region was chosen because it was the largest linked component. The embryo border was represented by a mask created using this area. The mask limits the extraction of TE features to the embryo region and helps in the removal of background noise.

2.6 Edge Enhancement Preparation

After using contrast limited adaptive histogram equalization and median filter the image has a high contrast and noise reduced representation. This makes the blastocyst's delicate structural elements easier to visualize. More dependable edge detection is made possible by the enhanced signal-to-noise ratio. Consequently, Trophectoderm cell borders may be precisely detected by the Canny edge detector. Canny edge detector enhances the extraction of TE features and reduces the impact of background noise.

2.7 Ensemble Learning Approach

In this study, the collected morphological features from the blastocyst images were used to classify Trophectoderm (TE) grades using an ensemble learning approach. The fitcensemble() function in MATLAB, which combines several weak learners to create a strong predictive model, was used to implement the model. Several base classifiers (such as decision trees) are trained on various subsets of the training data in order for the ensemble model to function. Different patterns in the feature space, such as edge density, circularity, texture, intensity and gradient information are captured by these distinct learners. All learners outputs are combined to create the final prediction, usually via weighted averaging or majority vote. The following handcrafted features were extracted from the TE region circularity, Mean intensity, Texture variation, Gradient strength and TE boundary distribution.

In comparison to a single classifier, this method increases robustness and decreases overfitting, this improves classification performance. The ensemble model in the suggested system successfully learns the correlation between TE grades (A, B, and C) and extracted characteristics, improving prediction accuracy on test data. By aggregating predictions from multiple classifiers, the model reduces over fitting and enhances stability. This results in more reliable in classification of TE grades.

2.8 Performance Evaluation

Determine the efficacy of the proposed system based on Ensemble Learning model for TE grading. Compare their results with those of conventional morphological assessment in terms of Confusion Matrix, accuracy, recall, precision, f1-score.

Table 2. Confusion Matrix

		Actual Values	
		Positive	Negative
Predicted Values	Positive	True Positive (TP)	False Positive (FP)
	Negative	False Negative (FN)	True Negative (TN)

$$Accuracy = \frac{\text{True Positive+True Negative}}{\text{True Positive+T} \quad \text{Negative+Fals} \quad \text{Positive+Fal} \quad \text{Netative}} \qquad (1)$$

$$Precision = \frac{\text{True Positive (TP)}}{\text{True Positive (TP)+}False\ Positive\ (FP)} \qquad (2)$$

$$Recall = \frac{\text{True Positive (TP)}}{\text{True Positive (TP)+}False\ Negative\ (FN)} \qquad (3)$$

$$f1 = 2 \text{ x } \frac{\text{Precision x Recall}}{\text{Precision+Rec}} \qquad (4)$$

Evaluating accuracy, recall, precision and f1 score involves using formulas Equations (1), (2), (3) and (4) [9] . An assessment categorization report is also utilized to calculate all of the above. In this study, we used Ensemble Learning model to grade the blastocyst on the feature trophctodem using a data set of 50 images. We conduct exploratory data analysis to discover patterns, to spot anomalies which included confusion matrix and data set description.

3. Result and Discussion

In this section, the performance of the proposed automated Trophectoderm (TE) grading framework is critically compared with previously published studies on blastocyst and TE assessment. Similarities and differences in methodologies, feature extraction techniques, classification approaches and performance metrics are discussed with appropriate citations. The advantages of the proposed method, including objective TE evaluation and reduced observer dependency.

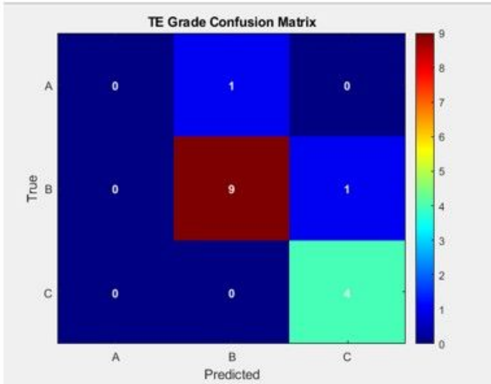
The findings of this study indicate that the proposed ensemble classifier had an accuracy 86.67%. Our results show a significant improvement in accuracy compared to earlier research. For instance, research by Marcus Vinicius Dantas et al. (2022) found that for grading TE Ridge Classification had given an accuracy of 57.69%[15], also research by Varsha R. et al. (2022) was found that by using Principal component Analysis (PCA) had an accuracy of 74.% and by using Linear Discriminant Analysis (LDA) had an accuracy of 76.00%, our study performs better than these earlier reports presented in Table 3.

Blastocyst images were used to test the suggested method, which combined feature extraction, segmentation, image preprocessing, and an ensemble learning model. Otsu's thresholding allowed for precise embryo segmentation, and preprocessing methods like grayscale conversion, Contrast Limited Adaptive Histogram Equalization (CLAHE) and median filtering enhanced image quality. Z-score normalization was used to extract and normalize five characteristics: edge density, circularity, texture, mean intensity and gradient mean. A 70–30 train-test split was used to train a bagging-based ensemble classifier. The model's overall accuracy was 73.33%. The confusion matrix demonstrates that the model performs best for Grade B and efficiently classifies high-quality embryos (Grade A).

There was some misclassification between Grades B and C, which suggests that borderline situations are challenging. When compared to single classifiers, the ensemble technique decreased overfitting and increased resilience. Although performance can be further enhanced with more datasets and more sophisticated models, the suggested method offers an objective and trustworthy approach for automated TE grading overall.

The performance of the proposed model was assess by using confusion matrix and standard classification metrics. The confusion matrix consists of three classes corresponding to TE grades A, B, and C. Using the testing dataset, the model's total accuracy was 73.33%. Class-wise analysis shows that Grade A attained a recall of 100%, meaning that all real Grade A embryos were accurately recognized, but with less accuracy because of a few false positives.

Trophectoderm (TE) grades A, B, and C were successfully classified using the suggested ensemble learning model; Grade B had the best classification accuracy with a precision of 0.88 and an F1-score of 0.78, while Grade A had perfect recall (1.00). Overall, the findings show that employing extracted image attributes, the suggested approach can accurately classify TE grades.



Class	Precision	Recall	F1-score	Support
A	0.50	1.00	0.67	1
B	0.88	0.70	0.78	10
C	0.60	0.75	0.67	4

Using a more simpler and interpretable machine learning framework rather than a computationally demanding deep learning model is the trade-off. This approach offers cheaper processing cost, easier implementation, better interpretability, and competitive grading accuracy for TE assessment, even though it might not be able to capture all complex visual patterns.

Fig 3. Confusion Matrix and Classification report Ensemble Learning Model

Table 3. Accuracy differentiation between other Model and this Model

Classifier	Accuracy
Ridge Classification (RC)	57.69%
Principal component Analysis (PCA)	74.00%
Linear Discriminant Analysis (LDA)	76.00%
Ensemble Classifier	86.67%

The main limitations of the proposed method involve its evaluation on a limited dataset, sensitivity to image quality variations, depends on handcrafted features, and the absence of multicenter validation. These factors may limits the generalizability of the model and represent important directions for future research.

4. Conclusion

This study presents an automated approach for Trophectoderm (TE) grading using image processing and an ensemble learning model. The proposed system effectively extracts morphological features and classifies embryos Grade with an accuracy of 86.67%. The results demonstrate good performance in identifying high-quality embryos, with some limitations in distinguishing borderline cases between Grades A and C. The use of quantitative features and ensemble learning provides a more objective and consistent alternative to manual grading. Overall, the method shows strong potential for supporting clinical decision-making in IVF. Future work can focus on larger datasets and advanced models to further improve accuracy and robustness.

The proposed study only focuses on Trophectoderm (TE) analysis, in contrast to earlier research that grades blastocysts using a combination of ICM, TE, and blastocoel features. For the suggested approach i.e. automated TE grading combines ensemble learning, edge-focused TE feature extraction, embryo masking, and CLAHE-based enhancement. This provides objective and repeatable TE evaluation while lowering computational complexity.

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