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A FUZZY LOGIC-BASED APPROACH FOR COLOUR VISION DEFICIENCY DIAGNOSIS

Ingrid Langer [1*], *Edit Laufer* [2]

1: https://orcid.org/0000-0001-5268-4692
2: https://orcid.org/0000-0001-8362-4334
[1,2] Institute of Mechatronics and Vehicle Engineering, Bánki Donát Faculty of Mechanical and Safety Engineering, Óbuda University, Hungary
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Abstract
A number of test methods have been developed to detect colour vision deficiency. The most commonly used colour vision tests (Ishihara test, Velhagen test) are simple and quick to detect anomalous colour vision, but most of them do not provide information on the type and severity of colour vision deficiency. The most accurate diagnosis can be achieved by anomaloscope. With this instrument, a numerical result expressing the type and severity of the colour vision deficiency can be obtained. The anomaloscope is a rather expensive instrument ($18,000), available only in a few ophthalmology practices, and the examination is tedious and requires competent staff. The aim of this study is to evaluate the results of a simple, rapid colour vision test using the proposed fuzzy inference system, which is suitable to replace the rather expensive anomaloscopy examination.

1 Introduction

Defective colour vision is a relatively common disorder, affecting mainly men. It is estimated that approximately 8% of men and 0.5% of women suffer from some form of colour vision deficiency, with red-green colour blindness being the most prevalent. Individuals with colour deficiency face significant challenges in everyday life, especially in environments where accurate colour discrimination is essential. This condition can lead to restrictions in professional opportunities, as colour vision plays a crucial role in various occupations such as aviation, maritime navigation, electrical work, and emergency services [1] [2].

The most widely used colour vision tests, such as the Ishihara test and Velhagen test, are effective in detecting the presence of colour vision deficiency but provide limited information regarding the severity and type of the deficiency. While these tests are simple, quick, and inexpensive, they fail to offer a precise numerical assessment of colour vision impairment. In contrast, the anomaloscope is considered the gold standard for diagnosing colour vision deficiencies, providing a detailed classification based on the type and severity of the condition. However, the anomaloscope is an expensive instrument, often costing around $18,000, and is available only in specialized ophthalmology clinics. Moreover, its operation requires trained personnel, and the testing process can be lengthy and demanding for the examinee.

Given these limitations, there is a need for an alternative method that combines the affordability and simplicity of pseudoisochromatic tests with the accuracy and quantitative output of the anomaloscope. The objective of this study is to develop a fuzzy inference system (FIS) that can enhance the diagnostic capability of an existing, cost-effective colour vision test. Specifically, we aim to evaluate the results of the Colorlite Atlas test using a fuzzy logic-based approach to produce a numerical result comparable to the anomaloscope’s anomalous quotient (AQ). By utilizing fuzzy

* Corresponding author. E-mail address: langer.ingrid@bgk.uni-obuda.hu

logic, which excels at handling imprecision and borderline cases, the authors propose a system that does not only determine the presence of colour deficiency but can also accurately categorize it based on severity and type.

This study explores the feasibility of implementing a fuzzy-based evaluation model, ensuring that colour vision deficiencies can be diagnosed more accurately and efficiently without the need for expensive instrumentation. The proposed approach has the potential to improve occupational health screenings and broaden access to precise colour vision diagnostics in various medical and professional settings.

The rest of the paper is organized as follows: In Section 2, various methods used for testing colour vision are presented. Section 3 introduces the fuzzy model developed for evaluating the results obtained with the Colorlite Atlas. In Section 4, the anomaloscope test results of 50 individuals with colour vision deficiency are compared to the results derived from the fuzzy evaluation of their Colorlite Atlas tests.

2 Colour vision test methods

Colour vision test methods can be classified into the following groups:

- Pseudoisochromatic tests (Ishihara test, Velhagen test, Dvorine test, Colorlite atlas)
- Colour discrimination or sorting tests (Farnsworth D15, Farnsworth-Munsell 100 hue test, Farnsworth desaturated test)
- Anomaloscope (Nagel, Heidelberg, Tomey)
- Lantern tests (Farnsworth lantern, Holmes-Wright lanterns)

The best-known pseudoisochromatic test, which is most commonly encountered in occupational health testing, is the Ishihara test (see Fig. 1) [3]. The essence of the test is to recognise a number or pathway, also made up of dots, in the centre of a circular field of coloured dots. The colours of the shapes and the background dots are chosen so that they are difficult or impossible to distinguish for defective colour vision persons, while for normal colour vision persons the numbers are easily recognisable. This test can quickly establish the fact of anomalous colour vision, but the result is of limited value in inferring the type and severity of colour deficiency.

Figure 1 Diagrams of the Ishihara test

The Colorlite colour vision testing atlas (Fig. 2), developed in-house by the Colorlite colour vision corrective lens company. This test is capable of a much more accurate diagnosis than the Ishihara test, but is less widely used, primarily for selecting colour vision correction lenses. The Colorlite test [5] [6] [7] has the advantage of being as simple and inexpensive as the Ishihara test, while being able to diagnose the type and severity of colour deficiency as well as the anomaloscope. The test involves the identification of so-called Landolt-C shapes, which are shapes made up of coloured dots before a backdrop of differently coloured dots. The figures are sorted by difficulty. The first figure in the row is the easiest, followed by progressively more difficult figures.

The test person has to view three different series, each with a different background colour and shape. In the R-G series, the Landolt-C is red and the background is made up of green dots. This series shows how serious the colour vision deficiency is. The P series shows the protos anomalies, and the D series the deuteros anomalies. The result of the test is the number written next to the first incorrectly recognized figure, which represents the average colour difference between the Landolt-C and the background. The R-G series of the Colorlite test distinguishes between severe, moderate and mild colour deficiency, while the P and D series distinguish between deutan (green) or protan (red) colour deficiency.

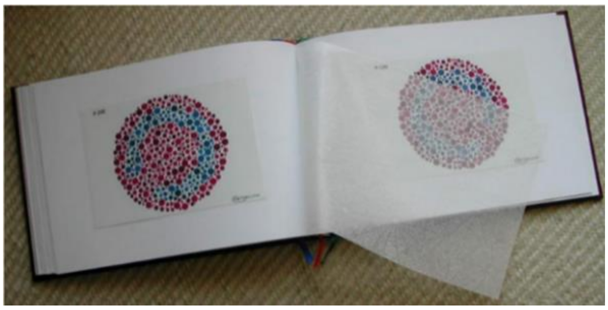

Figure 2 Colorlite Atlas

The most widely recognised colour vision testing instrument is the anomaloscope. It gives a numerical measurement and can be used to determine the type (protanomaly or deuteranomaly) and severity of colour aberration. The anomaloscope uses three monochromatic measuring lights, a red light of 662 nm, a green light of 549 nm and an orange light of 589 nm, to test colour vision according to DIN 6160. A split field of view shows a mixture of red and green on one side and orange on the other. The subject has to adjust the mixing ratio of red and green (R/G) and the intensity of orange light (Y) so that the two sides of the field of vision are seen as the same colour. The set values represent the result of the measurement. Normal colour vision users set it to R/G=45 +/- 5 divisions and Y=15 +/- 4 divisions. Green (so-called deuteranomal) colour vision readers set more green colour in the red-green mixture, and red (so-called protanomal) colour vision readers set more red. The adjusted R/G ratio is used to calculate the so-called anomalous quotient (AQ), a measure of colour vision and can be calculated as follows:

$$AQ = \frac{\frac{E-P}{P}}{\frac{E-M}{M}} \quad (1)$$

where E is the value of the R/G ratio, P is the set value of R/G ratio and M is the normal value of the R/G ratio.

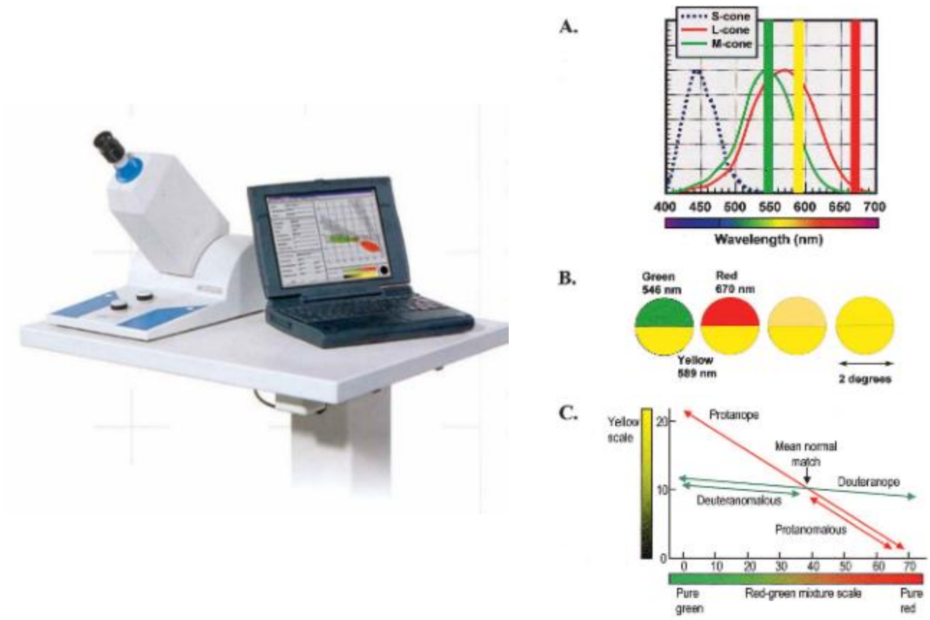

Figure 3 Anomaloscope

Table 1. Diagnosis according to AQ values

AQ	Diagnosis
<0,7	protanomaly
0,7…1,4	normal colour vision
>1,4	deuteranomaly

In domestic and international practice, anomaloscope is considered the most objective test method for diagnosing colour deficiency, but this measurement method also has some disadvantages. The instrument requires accurate and regular calibration. Proper knowledge and practice are required to operate the instrument. Achieving accurate colour matching requires a high degree of concentration and patience from the person being tested to. The test requires experience, without which misdiagnosis can easily occur [4].

3 The proposed fuzzy-based colour vision evaluation model

The diagnosis obtained with the Colorlite Atlas correlates well with the anomaloscope measurement results [7]. In occupational health, the anomaloscope measurement results are often the decisive factor in assessing suitability for the job. If an evaluation method can be developed for the Colorlite Atlas measurement results that correlates with the anomalous quotient (AQ) of the anomaloscope measurement, then the complex and expensive instrumental test could be replaced by a simple and rapid test method. Authors propose a fuzzy inference system to achieve this goal. In order to create the appropriate model Colorlite Atlas and anomaloscope measurement data were used.

The model was developed in Matlab Fuzzy Logic Designer environment. Mamdani evaluation was used in the fuzzy model, as it better models human reasoning by allowing rule outputs to be given by fuzzy membership functions. This approach has a high computational complexity, but it is not relevant in a non-real-time system. Great advantage of using fuzzy logic is its ability to handle subjectivity and imprecision of the data and evaluation process. It does not use sharp boundaries, so it can effectively handle potential borderline cases and transition ranges.

The structure of the rules in a Mamdani system is as follows. Let the input parameters be $x_1, x_2, \dots, x_n$ and the output is *y*. The general rule structure is as follows:

$$IF\ x_1 is\ A_{1,i_1} and \dots and\ x_n is\ A_{n,i_n} THEN y\ is\ B_{i_1,\dots,i_n} \qquad (2)$$

where A_{k,i_k} is the fuzzy set i_k belonging to input *k*, $B_{i_1,\dots,i_n}$ represents the consequents, $i_j = 1, \dots, n_j$, and n_j is the number of the sets belonging to input *j*.

The three inputs of the model correspond to the three sets of diagrams in the Colorlite Atlas (R-G, P and D). Three trapezoidal membership functions have been defined for each input by classifying the measurement results into 3 categories (severe, mild, normal). The output of the system gives the diagnosis of colour deficiency on a scale from -10 to 10, where -10 is the extreme value for deuteranomaly and 10 for protanomaly. The output range was covered by 7 triangular membership functions (severe, moderate and mild deuteranomaly, normal, mild, moderate and severe protanomaly).

The rule base of expert knowledge was set up using measurement data from colour deficient persons. This is shown in the table below:

Table 2 Rule base for fuzzy evaluation

	R/G normal			R/G moderate			R/G severe		
	D normal	D moderate	D severe	D normal	D moderate	D severe	D normal	D moderate	D severe
P normal	N	MiD	MoD	MiP	MoD	MoD	MoP	MoD	SD
P moderate	MiP	MoP	MoD	MoP	MoP	SD	SP	SP	SD
P severe	MoP	MoP	MoP	SP	SP	SP	SP	SP	SP

Abbreviations used in the table: **N**: normal colour vision, **MiD**: mild deuteranomaly, **MoD**: moderate deuteranomaly, **SD**: severe deuteranomaly, **MiP**: mild protanomaly, **MoP**: moderate protanomaly, **SP**: severe protanomaly.

The model was validated using a database of colour deficient persons, with data from both anomaloscope measurements and Colorlite Atlas measurements. The verification showed that the results of the fuzzy analysis did not give good values for the measurements that represent the borderline for deciding whether the subject is deuteranomalous or protanomalous. To overcome this problem, the fuzzy model had to be modified. Finally, modifying the membership functions of the inputs P and D yielded the expected result by tuning the parameters of the existing functions and adding a new membership function. In the modified model, 4 membership functions were used instead of 3 for the P and D inputs, and introduced a "mild deuteranomalous" and a "mild protanomalous" category to distinguish between diagnoses that are borderline cases (Fig. 6).

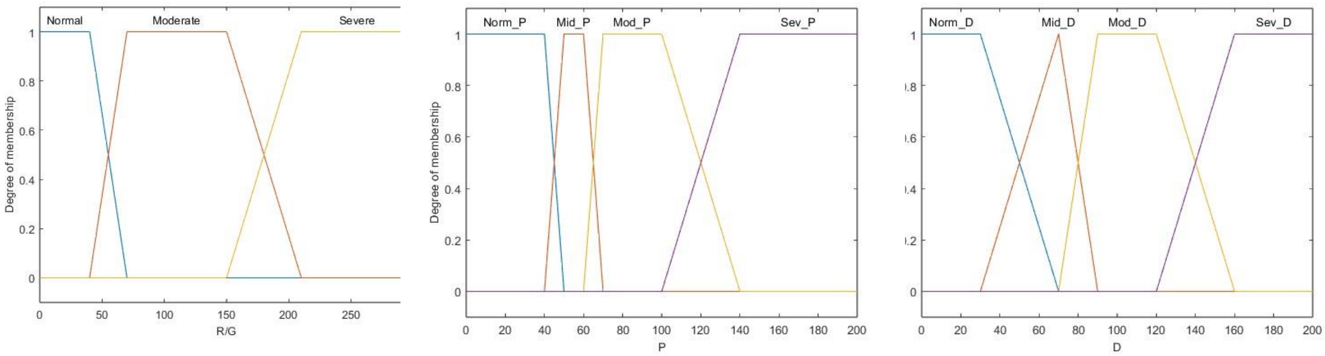

Figure 6. Membership functions of series R-G (left) and series P (middle) and series D (right)

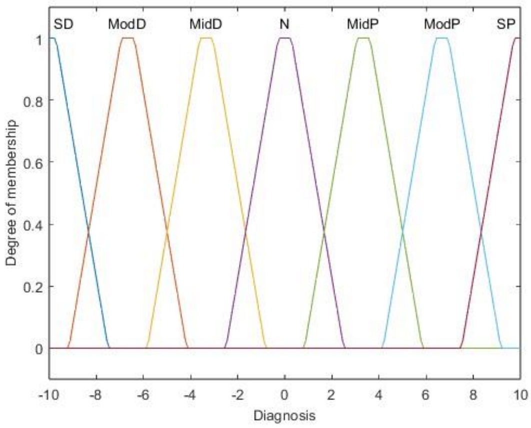

Figure 7. Membership functions of the output (diagnosis)

The increase in the number of membership functions also necessitated an extension of the set of rules set up. Instead of 27 rules in the original rule base, 48 rules were required to cover all cases. (Table 3)

Table 3 Rule base of the modified fuzzy model

	R/G normál				R/G moderate				R/G severe			
	P normál	**P mild**	**P moderate**	**P severe**	**P normál**	**P mild**	**P moderate**	**P severe**	**P normál**	**P mild**	**P moderate**	**P severe**
D normal	N	MiP	MoP	MoP	MiP	MiP	MoP	SP	MoP	MoP	SP	SP
D mild	MiD	MiP	MoP	MoP	MiD	MiP	MoP	SP	MoP	MoP	SP	SP
D moderate	MiD	MoD	MoP	SP	MiD	MiD	MoP	SP	MoD	MoP	SP	SP
D severe	MoD	MoD	MoD	SP	MoD	MoD	SD	SP	SD	SD	SD	SP

Abbreviations used in the Table 3: **N**: normal colour vision, **MiD**: mild deuteranomaly, **MoD**: moderate deuteranomaly, **SD**: severe deuteranomaly, **MiP**: mild protanomaly, **MoP**: moderate protanomaly, **SP**: severe protanomaly.

Applied operators are as follows:

- T-norm: min
- Aggregation: max
- Defuzzification: bisector

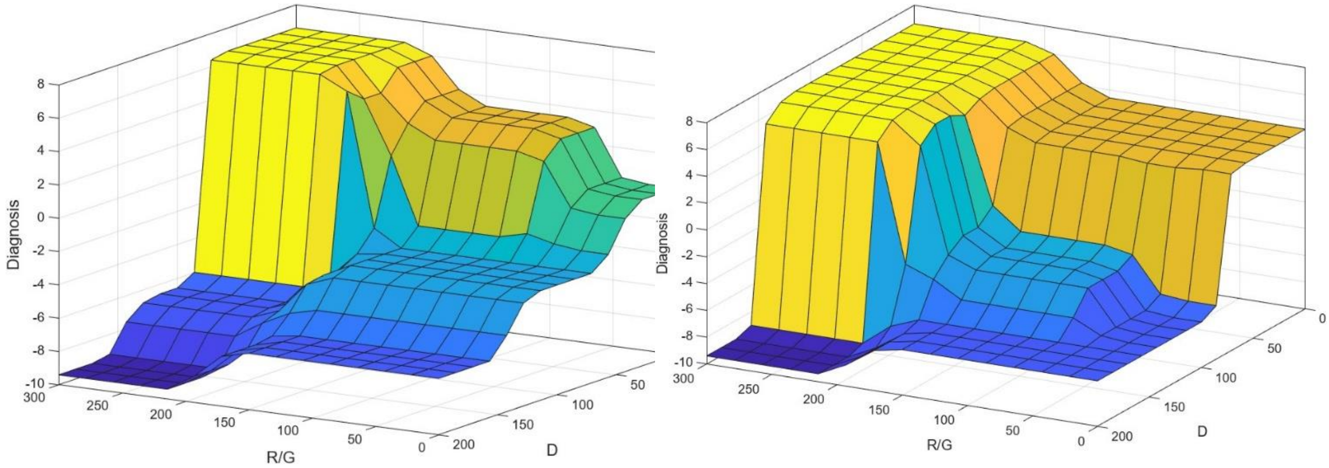

Figure 8 The output surface as a function of RG-D values at P=40 (left) and P=60 (right)

4 Verification of the results using the measurement results of colour deficient individuals

The verification was performed using the anomaloscope and Colorlite Atlas measurement results of colour deficient individuals. The database is derived from the anonymized measurement data of 50 individuals aged between 14 and 65 years, who applied for a color vision correction assessment. The results are shown in Table 4.

In the table, subjects who were found to be protanomalous based on the anomalous quotient and fuzzy analysis results are highlighted in pink, and the deuteranomalous ones are highlighted in green. For comparison, the second column of the table also contains the results of the Ishihara test, a series of 20 digits showing the numbers correctly identified (the Ishihara test is usually only used to determine colour deficiency, with a maximum of 1-2 mistake allowed, and a person scoring worse than this is considered to be a colour mismatch)

It can be observed that the results of the anomaloscope and the fuzzy analysis do not match for subjects 5, 12, 21, 36, 27 and 45. The result of the anomaloscope measurement for subject 5 shows a colour deficiency, while the fuzzy analysis diagnoses normal colour vision. For subjects 12, 21, 36, the reverse is true, with anomaloscope showing normal colour vision and fuzzy analysis showing colour mismatch. However, in all 4 cases, the third test method, the Ishihara test, confirms the fuzzy analysis, i.e. the discrepancy could be due to the error of the anomaloscope measurement. A real discrepancy is only observed in 2 cases, for subjects 27 and 45. In the case of subject 27, the anomaloscope shows a mild deuteranomaly, the fuzzy analysis shows a mild protanomaly, while subject 45 was found to be protanomalous on the anomaloscope, but with Colorlite Atlas and thus the fuzzy analysis, the result was normal. This represents only 4% of the cases examined, which means that the modified fuzzy model meets expectations.

Table 4 Comparison of fuzzy analysis results with real measurement data

Person	Ishihara	anomaloscope			Colorlite Atlas			Fuzzy
		R/G	Y	AQ	R/G	P	D	
1	3	60	12,4	0,26	300	40	40	6,6
2	3	10	19,8	7,64	300	40	140	-7,4
3	10	15,5	21,5	4,50	80	40	60	-3,4
4	3	49,5	13,6	0,58	240	40	0	6,6
5	20	14,5	19,1	4,89	0	0	0	0
6	11	66,4	4,9	0,12	100	40	40	2,3
7	13	16,6	16,1	4,12	60	40	140	-5
8	14	25,8	15	2,22	80	0	200	-6,6
9	4	59,3	9	0,28	140	40	80	-3,4
10	20	23,2	16,1	2,60	40	40	40	-0,6
11	4			protanope	200	40	0	6,4
12	5	40	15	1,00	220	40	30	6,6
13	15			deutertanope	220	0	200	-9,4
14	3	65	4,9	0,15	120	40	40	2,6
15	7	63	7,1	0,19	100	30	40	2,6
16	2	65	5,3	0,15	140	0	40	2,6
17	15	27,5	15,2	2,01	80	60	100	-3,4
18	5	9,7	18,5	7,91	280	100	200	-9,4
19	3	5,2	19,6	15,80	220	0	200	-9,4
20	2	65	6,2	0,15	260	60	40	6,6
21	11	40	11	1,00	80	0	200	-6,6
22	7			deutertanope	100	0	200	-6,6
23	16	16	17,1	4,32	40	40	60	-2,8
24	15	12	19,9	6,16	60	40	60	-2
25	5	12,3	18,9	5,98	80	0	80	-3,4

Person	Ishihara	anomaloscope			Colorlite Atlas			Fuzzy
		R/G	Y	AQ	R/G	P	D	
26	2	56,1	10,6	0,37	180	60	60	5
27	13	21,8	15,9	2,85	120	60	60	3,4
28	6			deutertanop	300	40	200	-9,4
29	4	67,8	5,1	0,09	160	40	40	3
30	20	24,3	16,2	2,43	60	0	60	-2
31	4	33,3	17,8	1,45	40	0	200	-6,6
32	5	66,4	9,7	0,12	60	40	40	1,8
33	5	21,5	16,4	2,90	60	60	140	-5
34	4	67,3	4,6	0,10	80	40	40	2,6
35	11	60	7,9	0,26	60	40	40	1,8
36	3	40	17	1,00	280	140	60	9,2
37	6	62,1	5,3	0,21	100	60	60	3,4
38	4	52,1	10,6	0,49	60	40	40	1,8
39	2	65	6,5	0,15	260	40	60	6,6
40	2	61	7,9	0,24	200	40	40	5,8
41	7	65	4,6	0,15	80	40	40	2,6
42	15	61,5	6,9	0,23	60	60	40	3,4
43	4			protanope	240	40	0	6,6
44	13	56,1	10,9	0,37	80	80	60	6,6
45	6	65	5,8	0,15	40	40	30	0
46	2	60	8,6	0,26	280	0	60	6,6
47	13	5	15	16,48	80	60	100	-3,4
48	3	65	6,5	0,15	240	40	40	6,6
49	19	28,6	15	1,88	40	40	60	-1,6
50	8	65	7,2	0,15	60	0	0	2,4

5 Conclusion

In this study, the authors proposed a fuzzy inference system to enhance the diagnostic capabilities of the Colorlite Atlas test, aiming to bridge the gap between traditional pseudoisochromatic tests and the high-precision but costly anomaloscope. Our findings indicate that the fuzzy-based evaluation model can provide a numerical assessment of colour vision deficiency that correlates well with anomaloscope measurements. Based on the results the proposed approach could serve as a viable alternative for diagnosing colour vision deficiencies with improved accuracy and accessibility.

The most significant outcome of this research is that the proposed fuzzy logic-based approach can improve colour vision testing by providing a cost-effective, rapid, and reliable method for assessing colour vision deficiencies, thereby benefiting both occupational health screenings and clinical diagnostics.

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