OPTIMIZING PIGMENT PRODUCTION FROM AGRICULTURAL WASTE USING METAHEURISTIC-BASED ALGORITHMS

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DEDICATION

This thesis is special dedicated to:

My beloved husband, Che Rasnan Bin Che Rashid

My beloved baby, Muhammad Thaqif Ubaidullah Bin Che Rasnan

My beloved parents, Saleha Binti Ahmad and Suhaimi Bin Jaafar

My beloved siblings, families and friends

For their endless love, support, courage and understanding

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ABSTRACT

Due to the uncontrolled industrial applications of synthetic pigments that can cause a serious hazard to human health and the environment, the scientific community skewed towards natural colors. The simplest and efficient method to increase pigment production is by manipulating the medium. Among classical and statistical methods, one factor at a time and response surface methodology (RSM) is the most widely used in medium optimization. However, the main drawback of these methods is tedious wet experiments need to be conducted to predict the output for a new input data and prior to data processing and analytic for decision making. In the past few years, the rapid advances in the field of metaheuristic optimization algorithm have provided a solution in optimization problems. In this study, metaheuristic optimization scheme, together with the mathematical model which is regression analysis have been implemented to minimize time and cost of wet-lab experiments by increasing the pigment productions using the proposed compact experiments. Moreover, the predictive optimization performance and sensitivity analysis of metaheuristic algorithm have been evaluated to validate the results, and the authenticity has been proven by wet laboratory experiments. Analysis of the optimization showed that the percentage improvement for the proposed compact experiment which is particle swarm optimization (PSO) model improved from RSM model by 1.32%, while the percentage improvement for all compact experiments was better than multiple polynomial model (MPR) model with the highest PSO percentage of 2.0507%. Hence, the experimental findings revealed that, the metaheuristic-based approach successfully predicted the optimum fermentation parameters condition and concentration with better achievement on pigment production by using proposed compact experiment.

ABSTRAK

Disebabkan industri sintetik pigmen yang tidak terkawal yang boleh menyebabkan bahaya yang serius terhadap kesihatan manusia dan alam sekitar, komuniti sains beralih kepada warna semulajadi. Kaedah yang paling mudah dan berkesan untuk meningkatkan pengeluaran pigmen adalah memanipulasi medium. Di antara kaedah klasik dan statistik, satu faktor pada satu masa dan kaedah rangsangan permukaan adalah yang banyak digunakan dalam pengoptimuman medium. Walau bagaimanapun, kelemahan utama kaedah ini adalah banyak eksperimen basah yang perlu dilakukan untuk meramal keputusan untuk input data baru dan sebelum pemprosesan data dan analitik untuk membuat keputusan. Dalam beberapa tahun kebelakangan ini, kemajuan pesat dalam bidang algoritma pengoptimuman metaheuristik memberikan penyelesaian dalam masalah pengoptimuman. Dalam kajian ini, skema pengoptimumam metaheuristik berserta model matematik iaitu analisis regresi telah dilaksanakan untuk meminimumkan masa dan kos eksperimen makmal basah dengan meningkatkan pengeluaran pigmen menggunakan eksperimen kompak yang dicadangkan. Tambahan pula, prestasi ramalan pengoptimuman dan analisis kepekaan algoritma metaheuristic telah dinilai untuk mengesahkan hasilnya, dan kesahihannya telah dibuktikan oleh eksperimen makmal basah. Analisis pengoptimumam menunjukkan peningkatan peratusan bagi cadangan eksperimen kompak iaitu Pengoptimuman Kawanan Zarah (PSO) meningkat daripada model RSM sebanyak 1.32%, manakala peratusan peningkatan bagi semua eksperimen kompak adalah lebih baik daripada Model Regresi Polinomial (MPR) dengan peratusan tertinggi PSO sebanyak 2.0507%. Oleh itu, penemuan eksperimen menunjukkan bahawa dengan menggunakan ekspermen kompak yang dicadangkan, pendekatan berasaskan metaheuristik berjaya meramalkan keadaan dan kepekatan fermentasi parameter yang optimum dengan pencapaian yang lebih baik pada pengeluaran pigmen.

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LIST OF ABBREVIATIONS

ABC	-	Artificial Bee Colony
ANN	-	Artificial Neural Network
ANOVA	-	Analysis of Variance
BA	-	Bat Algorithm
BBD	-	Box-Behnken Design
BPNN	-	Back Propagation Neural Network
CCD	-	Central Composite Design
CS	-	Cuckoo Search
DE	-	Differential Evolution
DF	-	Degree of Freedom
DOE	-	Design of Experiment
FA	-	Firefly Algorithm
GA	-	Genetic Algorithm
MAE	-	Mean Absolute Error
MOGA	-	Multi-Objective Genetic Algorithm
MPR	-	Multiple Polynomial Regression
MS	-	Mean Square
MSE	-	Mean Square Error
OFAT	-	One Factor at A Time
PE	-	Percentage Error
PI	-	Percentage Improvement
PSO	-	Particle Swarm Optimization
RMSE	-	Root Mean Square Error
RSM	-	Response Surface Methodology
SS	-	Sum of Square
UTM	-	Universiti Teknologi Malaysia

LIST OF SYMBOLS

A	-	Loudness
Adj- R^2	-	Adjusted R-squared
C_1	-	Cognitive
C_2	-	Social Acceleration
CR	-	Crossover Probability
d	-	Dimension
F	-	Scaling Factor
fmin	-	Minimum Frequency
fmax	-	Maximum Frequency
I	-	Intensity
n, NP	-	Population Size
Pa	-	Probability
Pred- R^2	-	Predicted R-squared
r	-	Pulse Rate
r1, r2, rand	-	Random Number
R^2	-	R-squared
tmax	-	Maximum Iteration
w	-	Inertia Weight
α	-	Step Size
β	-	Random vector
β_0	-	Attractiveness
ε	-	Step size of random walk
γ	-	Absorption
λ	-	Levy Exponent

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CHAPTER 1

INTRODUCTION

1.1 Overview

Currently, pigments are widely used in many industries such as painting, food, fabric, cosmetic and many more. Pigment is a substance or material that can change color. However, most industries used synthetic pigments that can be hazardous to human health and also environment. This has led to increased demand in pigments derived from natural sources such as plants, animals and also microorganism. Compared to plant and animal, pigments from microorganism such as bacteria are much cheaper and can easily be found. Bacteria can nearly be found in almost any place, where there is a conducive environment for them to survive. Besides that, bacteria offer certain advantages based on its flexibility, short life cycle and simple propagation technique compared to plants and animals.

Nowadays, producing quality organic pigments is hampered by the high cost of production. In view of this, various studies have been carried out to explore other types of media which are cheaper and easily available such as agricultural waste materials (Venil et al., 2014). Besides that, the use of these agricultural wastes in pigments bioprocess can also reduce its environmental impact (Venil et al., 2014). Agricultural waste is waste produced on agricultural premises as a result in an agricultural activity. Agricultural waste is one of the places where bacteria grow rapidly and can easily be found. Some bacteria that thrive in these premises are capable to produce pigments such as *Chromobacterium Violaceum* (violet pigment), *Chryseobacterium artocarpi* (yellowish-orange pigment) and *Serratia marcescens* (red pigment).

However, bacteria that grow in this agricultural waste have adapted with the surrounding environment, where this environmental condition and nutrients are essential for bacteria to grow and reproduce. Bacteria have adapted to the habitats most suitable for their requirements in the natural environment (Ajdari et al., 2013). The effects of various nutritional factors are important in order to determine their influence on pigment production. The use of different growth media, directly affect the growth and production of pigments. Appropriate medium growth of bacteria for the optimum production of pigment is needed to achieve better pigment production. According to Zahra et al. (2012), the simplest and most efficacious strategy to increase the yield and productivity is the manipulation of nutritional requirements. Thus, medium optimization is important to improve the number of pigments production.

Among statistical techniques, response surface methodology (RSM) is the most widely used methods in media optimization today (Lim et al., 2021). However, computational techniques inspired by biological phenomenon have been dramatically increased where it provides solution for many complex optimization problems. Biological inspired evolutionary algorithm also includes metaheuristic optimization algorithm. Hence, metaheuristic optimization algorithms such as particle swarm optimization (PSO), genetic algorithm (GA), differential evolution (DE), cuckoo search algorithm (CS), firefly algorithm (FA) and bat algorithm (BA) are used in this research. Metaheuristic algorithm has been one of the most prosperous technologies and is considered as one of the alternative tools to optimize pigment production, besides overcoming the drawback of the limitation of the classical method that have been discussed in detail in many earlier reports. Due to the limitation of the classical method, which requires tedious number of experiments, this study proposed compact wet laboratory experiments.

Furthermore, metaheuristic algorithms will be applied in order to optimize the pigment production for the standard wet laboratory (wet-lab) experiments. The optimal metaheuristic process is proposed to increase the pigment productions through compact wet-lab experiments. The rationale of proposing this study is given in the background of the study followed by the objectives of the study, its significance and the scope of the research. Subsequent sections explicate the limitations of the classical method which lead to compact experiment discussed in next section.

1.2 Background of the Study

Nowadays synthetic colors are utilized in most industries including food, cosmetic, clothing, painting, pharmaceutical, and many more. In the past, synthetic pigments are widely used and popular because of their stability and low cost. However, uncontrolled industrial application of synthetic pigments can be hazardous to human health and the environment. Additionally, synthetic pigments can cause problems since the chemical compounds that make good pigments are also toxic. Concern over the potential toxicity of some synthetic pigments that can cause hazard has led interest in pigments derived from natural sources. In last decades, there has been an increasing trend towards replacement of synthetic pigments with natural pigments because of the strong consumer demand for more natural products.

The major obstacles of producing quality organic pigments are normally hampered by the high production cost. Cost production is the most critical and primary focus in the industries in their effort increase production with low cost. Facing with the rising production cost and the competition in global industries in term of quality and price, the trend is shifting towards manufacturing pigments from bio-degradable materials such as agricultural waste. In recent years, utilization of agriculture gains more importance in bioprocess industries because of high nutrient content and low cost. Thus, pigments from the agricultural waste are the solution as they are environmentally friendly and save the production cost. In addition, there are some bacteria such as *Chromobacterium Violaceum* (violet), *Chryseobacterium artocarpi* (yellowish-orange), *Serratia Marcescens* (red), *Monascus sp*. (yellow, orange and red), *Gardenia jasminoides var. radicans* (yellow), *Rhodotorula mucilaginosa* (green and red) and others, that thrive in these agricultural wastes and produce pigments by fermentation process.

However, there are many types of conditions that affect the fermentation process of pigment production because each bacterium has its own special conditions. This is because the bacteria that grow in this agricultural waste have adapted to the surrounding environment, where this environmental condition and nutrients are essential for bacteria to grow and reproduce. Hence, the use of different concentration of nutrient growth directly affects the growth and production of the pigment. Therefore, the modeling and optimization of fermentation process is important to achieve the optimal concentration of nutrient growth that increases the pigment production.

As stated by Lopes and Ligabue-Braun (2021), medium optimization is the most important to maximize the production. The most critical problem on medium optimization is it involves large number of experiments, time consuming, high labour cost and is an open-ended experiment (Singh et al., 2017). In earlier time, the optimization of medium generally used one factor at time (OFAT) method. However, OFAT requires a large number of experiments which leads to time, reagents and material consumption as well as experiments expenses, especially when a large number of input variables are involved. OFAT method involves changing one variable at a time while fixing other variables at certain level (Poorniammal, Gunasekaran & Murugesan, 2015; Saini et al., 2020). Therefore, optimal conditions may be missed because this method ignores interaction among the different medium components (Pal et al., 2009). Furthermore, all experiments generated from OFAT design need to be carried out to obtain the highest pigment production, and they are time consuming and incur higher cost. Thus, extensive research has been focused on cheaper methodologies and efforts have been made in order to reduce the production cost and time (Korumilli & Mishra, 2014). In the past few decades, statistical method such as Factorial design, Taguchi method and response surface methodology (RSM) have been used to overcome the drawback of OFAT method.

Recently, experimental design such as response surface methodology (RSM) is the most widely used in medium optimization (Venil, Dufossé & Renuka Devi, 2020). Even though RSM is widely used with much success, there are some limitations associated with RSM. Some literature also shows that by using RSM, tedious number of experiments need to be conducted to find the optimal solution. The prediction of response based on second-order polynomial equation in RSM is often limited to low levels and results in poor estimation of the optimal formulation (Singh et al., 2017). Therefore, the use of alternative optimization technique for finding the true optimal is needed due to the limitation of boundary parameters in RSM. In addition, RSM also has a limitation in designing the objective function (Venil et al., 2020). The reliability of RSM will be confronted by the interaction between the factors and the response, which increases the difficulty of the study (Pal et al., 2009; Venil et al., 2020).

Based on the previous studies, regression analysis is the easiest way to interpret and organized the fermentation parameters and design the objective function. The developed model for the fermentation process is a mathematical equation that shows the relationship between two parameters, process parameters (input variables) and fermentation performance (responses). In addition, the rapid advances in the field of soft computing technique such as metaheuristic optimization algorithm also have higher potential to provide solution in optimization problem. Soft computing techniques generally include the metaheuristics algorithm such as genetic algorithm (GA) (Goldberg, 1989), differential evolution (DE) (Gao et al., 2010), bat algorithm (BA) (Yang & He, 2013), firefly algorithm (FA) (Yang & He, 2013), cuckoo search (CS) (Gandomi, Yang & Alavi, 2013), and particle swarm optimization (PSO) (Kennedy and Eberthart, 1995). These metaheuristic techniques are easy to implement and have good local search ability. From the related studies, regression analysis together with metaheuristic optimization algorithm has been successfully applied in fermentation process to optimize and accurately predict the optimal solutions. For example, the optimization of the yellow pigment (Sharmila et al., 2019; Wu et al., 2021 & Liu et al., 2021) red pigment (Ismail et al, 2021; Shetty et al., 2021; Asghari et al., 2021), orange pigment (Venkatachalam et al., 2021), lipase (Chauhan et al., 2013 & de Menezes et al., 2021), cellulase (Bezerra et al., 2021) and ethylene (Jahromi et al., 2018) production, respectively. However, there has been no scientific research done on the production of flexirubin (yellowish-orange pigment) using metaheuristic algorithm such as PSO, BA, FA, CS, GA and DE with compact experiment.

Hence, a cost-effective metaheuristic approach is proposed in this study to improve the procedures of the conventional wet-lab experiments with a compact wet-lab experiments. Compact experiment in this study is defined as smaller number of wet laboratories experiment together with the optimal fermentation parameters. In addition, the predictive optimization performance and sensitivity analysis will be implemented for the result validation followed by the wet-lab experiments for further verification.

1.3 Problem Statement

The most important issue regarding natural pigment is the price of final product which is more expensive than synthesized color. Thus, the fermentation product cost could be reduced by cheaper sources such as bacteria together with optimization strategy. Furthermore, a proper growth medium for the optimum production of pigment is needed for better pigments production. Currently, the implication of different growth medium directly affects the production of pigment. This is because the bacteria have to adapt to certain environmental condition and nutrient as source of energy. Currently, one factor at time (OFAT) and statistical method such as RSM, factorial design and Taguchi method have been used extensively to solve this problem. However, the are some limitations of the statistical method that have been discussed in earlier reports, whereby tedious experiments are required and both methods are incapable to find the optimal solution. Hence, metaheuristic optimization algorithm is implemented in this study in order to achieve the optimal pigment production while minimizing the time and cost.

Thus, the following issues need to be addressed as stated below;

1) Could the problem of pigmentation bio-process be solved using metaheuristic optimization algorithm?

2) How to implement metaheuristic optimization algorithm in fermentation process of pigmentation?

3) Could the metaheuristic algorithm improve the efficiency of the pigment productions problem?

4) Could metaheuristic algorithm compact the experiments (minimize experiments) for pigment production?

1.4 Research Aim

The aim of the study is to propose metaheuristic optimization scheme for Chryseobacterium artocarpi bacteria (in agricultural waste) and to obtain the optimized pigment production (flexirubin) and minimizing the time (experiments) and cost using cost-effective metaheuristic analysis through compact experiment.

1.5 Objective of the Research

In order to achieve the answers to the above questions, the objectives of this study have been identified as:

1) To propose metaheuristic optimization scheme for pigments production and develop mathematical model of pigment parameters for optimal concentration.

2) To design compact experiments for cost-effective pigment production for the proposed scheme.

3) To validate the proposed scheme with the wet laboratory experiments based on the optimal solutions from the compact experiment.

1.6 Scope of the Study

To achieve the above objectives, the scope of this study is bound to the following:

1) Bacteria from the agricultural waste are selected to produce quality pigment (natural sources) for production of flexirubin (yellowish-orange pigment).

2) Bacteria strain C. artocarpi CECT 8497T (=KCTC 32509T) used in the present work was procured from an orchard at Universiti Teknologi Malaysia (UTM), Skudai, Malaysia.

3) Focusing on finding optimum medium fermentation of Chryseobacterium artocarpi bacteria.

4) Using metaheuristic optimization algorithm.

5) Using Matlab to develop the metaheuristic algorithms and visualization.

6) Using Minitab and SPSS to analyze the statistical analysis of the results.

1.7 Significance of the Study

This study investigates the capabilities of cost-effective metaheuristic optimization scheme to increase the pigment production through compact wet laboratory experiments. Moreover, the solution can be obtained by using the ideal parameters with a limited number of experiments, minimize the time and cost of wet-lab experiments through the proposed compact experiments. Consequently, the proposed solution could be new research area for the fermentation process engineering community to explore more on advance metaheuristic methods in dealing with cost-effective solutions. This is due to the proposed method which is so-called cost-effective compact experiment would be the first scheme on fermentation optimization for the pigment production.

1.8 Thesis Outline

This thesis consists of six chapters, which include chapter one (introduction), chapter two (literature review), chapter three (research methodology, mathematical modeling and metaheuristic optimization), chapter four (compact experiment) and chapter five (conclusion and future work), respectively.

Chapter 1 contains an introduction, background of the problem, problem statement, aim, objective scope of the research and research significant of the study.

Consequently, Chapter 2 presents the literature review of the study includes the review of the pigment, modeling, optimization, compact experiment and related works. Chapter 3 presents the framework of the study and methods to the research problem. The schematic of metaheuristic implementation on pigment production also been presented in this chapter. Furthermore, Chapter 3 discusses on the modeling process of the preliminary experimental data using regression analysis method. The predictive analysis of the metaheuristic algorithms also explains in this chapter. In addition, Chapter 4 describes the optimization of metaheuristic techniques and the proposed compact experiments including the discussion on the result and analysis. Finally, Chapter 5 highlights the findings and contributions of the research work, consequently, provides suggestions and recommendations for the future study of research.

REFERENCES

Abd El Aty, A. A., Wehaidy, H. R. and Mostafa, F. A. (2014) 'Optimization of inulinase production from low cost substrates using Plackett–Burman and Taguchi methods', *Carbohydrate Polymers*, 102, pp. 261-268.

Ahmad, W. A., Yusof, N. Z., Nordin, N., Zakaria, Z. A. and Rezali, M. F. (2012) 'Production and characterization of violacein by locally isolated Chromobacterium violaceum grown in agricultural wastes', *Applied Biochemistry and Biotechnology*, 167(5), pp. 1220-1234.

Ajdari, Z., Ebrahimpour, A., Manan, M. A., Ajdari, D., Abbasiliasi, S., Hamid, M. and Ariff, A. B. (2013) 'Nutrients interaction investigation to improve Monascus purpureus FTC5391 growth rate using response surface methodology and artificial neural network', *Malaysian Journal of Microbiology*, 9(1), pp. 68-83.

Alonso, M. C., Bousbaine, A., Llovet, J. and Malpica, J. A. (2011) 'Obtaining industrial experimental designs using a heuristic technique', E*xpert Systems with Applications*, 38(8), pp. 10094-10098.

Aruldass, C. A., Aziz, A., C. K., Khasim, A. R. and Ahmad, W. A. (2016) 'Utilization of agro-industrial waste for the production of yellowish-orange pigment from Chryseobacterium artocarpi CECT 8497', *International Biodeterioration & Biodegradation*, 113, pp. 342-349.

Asghari, M., Jahadi, M., Hesam, F. and Ghasemi-Sepro, N. (2021) 'Optimization of Monascus pigment production on date waste substrates using solid state fermentation', *Applied Food Biotechnology*, 8(3), pp. 247-254.

Behera, B. K. and Varma, A. (2017) Microbial Biomass Process Technologies and Management. Springer.

Beheshti, Z., Shamsuddin, S. M. H. and Hasan, S. (2013) 'MPSO: median-oriented particle swarm optimization', *Applied Mathematics and Computation,* 219(11), 5817-5836.

Beheshti, Z. and Shamsuddin, S. M. (2015) 'Non-parametric particle swarm optimization for global optimization', *Applied Soft Computing*, 28, pp. 345-359.

Baishan, F., Hongwen, C., Xiaolan, X., Ning, W. and Zongding, H. (2003) 'Using genetic algorithms coupling neural networks in a study of xylitol production: medium optimization' *Process Biochemistry*, 38(7), pp. 979-985.

Banerjee, D., Mondal, A., Gupta, M., Guha, A. K. and Ray, L. (2014) 'Optimization of fermentation conditions for green pigment production from Bacillus cereus M116 (MTCC 5521) and its pharmacological application', *Letters in Applied Microbiology,* 58(1), pp. 25-30.

Bezerra, C. O., Carneiro, L. L., Carvalho, E. A., das Chagas, T. P., de Carvalho, L. R., Uetanabaro, A. P. T., da Silva, G. P., da Silva, E. G. P. and da Costa, A. M. (2021) 'Artificial intelligence as a combinatorial optimization strategy for cellulase production by Trichoderma stromaticum am using peach-palm waste under solid-state fermentation', *BioEnergy Research*, pp. 1-10.

Chaskes, S., Cammer, M., Nieves, E. and Casadevall, A. (2014) 'Pigment production on L-tryptophan medium by Cryptococcus gattii and Cryptococcus neoformans', *PloS One*, 9(4), p. e91901.

Chauhan, M., Chauhan, R.S. and Garlapati, V.K. (2013) 'Modeling and optimization studies on a novel lipase production by Staphylococcus arlettae through submerged fermentation', *Enzyme Research*.

Chen, F., Xing, C., Huo, S., Cao, C., Yao, Q. and Fang, P. (2016) 'Red pigment content and expression of genes related to anthocyanin biosynthesis in radishes (Raphanus sativus L.) with different colored flesh', *J. Agric. Sci*, 8(126), pp. 10-5539.

da Costa, J. P. V. and Vendruscolo, F. (2017) 'Production of red pigments by Monascus ruber CCT 3802 using lactose as a substrate', *Biocatalysis and Agricultural Biotechnology,* 11, pp. 50-55.

Darwesh, O. M., Matter, I. A., Almoallim, H. S., Alharbi, S. A. and Oh, Y. K. (2020) 'Isolation and optimization of Monascus ruber OMNRC45 for red pigment production and evaluation of the pigment as a food colorant', *Applied Sciences,* 10(24), p. 8867.

Daud, N. F. S., Said, F. M., Yasin, N. H. M. and Zahari, M. A. K. M. (2021) 'Optimization of Red Pigment Production by Solid State Fermentation Using Oil Palm Frond', *Materials Science Forum*, 1025, pp. 150–156.

Delgado-Vargas, F. (2002) Natural colorants for food and nutraceutical uses. CRC press.

Elkenawy, N. M., Yassin, A. S., Elhifnawy, H. N. and Amin, M. A. (2017) ‘Optimization of prodigiosin production by Serratia marcescens using crude glycerol and enhancing production using gamma radiation’, *Biotechnology Reports,* 14, pp. 47-53.

Garlapati, V. K., Vundavilli, P. R. and Banerjee, R. (2010) ‘Evaluation of lipase production by genetic algorithm and particle swarm optimization and their comparative study’, *Applied Biochemistry and Biotechnology*, 162(5), pp. 1350-1361.

Garlapati, V. K., Vundavilli, P. R. and Banerjee, R. (2017) ‘Optimization of flavor ester production through artificial bee colony algorithm: ABC optimization approach for flavor ester production’, *2017 4th International Conference on Image Information Processing, ICIIP 2017,* 2018-January, pp. 1–4.

Gao, Y., Zhou, J. and Jia, S. (2010) 'A New Multi-Objective Differential Evolution Algorithm', *Proceedings - International Conference on Computational Intelligence and Security,* IEEE, pp. 170-173.

Gandomi, A. H., Yang, X. S. and Alavi, A. H. (2013) 'Cuckoo search algorithm: a metaheuristic approach to solve structural optimization problems', *Engineering with computers*, 29(1), pp. 17-35.

Goldberg, D. E. (1989) Genetic algorithm in search, optimization, and machine learning. New York: Addison-Wesley.

Hadiyat, M. A. and Wahyudi, R. D. (2013) ‘Integrating steepest ascent for the Taguchi experiment: A simulation study’, *International Journal of Technology,* 3, pp. 280-287.

Hamid, N. F. and Said, F. M. (2016) ‘Factorial design screening for the red pigment production by Monascus purpureus FTC 5356’, *Jurnal Teknologi,* 78(11-2).

Hamouda, R. A., Al-Saman, M. A., El-Sabbagh, S. M., Abo El-Seoud, G. W. and Hendawy, A. N. (2017) ‘Approach to improve the productivity of bioactive compounds of the cyanobacterium Anabaena oryza e using factorial design’, *Egyptian Journal of Basic and Applied Sciences*, 4(3), pp. 190-195.

Hao, L., Li, H. and Lin, J. M. (2017) ‘Fractional factorial design based microwave-assisted extraction for the determination of organophosphorus and organochlorine residues in tobacco by using gas chromatography—mass spectrometry’, *Journal of Separation Science,* 40(2), pp. 542-549.

Heredia-Guerrero, J. A., Heredia, A., Domínguez, E., Cingolani, R., Bayer, I. S., Athanassiou, A. and Benítez, J. J. (2017) 'Cutin from agro-waste as a raw material for the production of bioplastics', *Journal of Experimental Botany*, 68(19), pp. 5401-5410.

Ismail, G. A., Fitriana, A. D. and Sukandar, U. (2021) 'Medium optimization for production of Monascus Purpureus pigment through solid-state fermentation', *IOP Conference Series: Materials Science and Engineering*, 1143(1), p. 012019.

Jahromi, F. S., Beheshti, M. and Rajabi, R. F. (2018) 'Comparison between differential evolution algorithms and response surface methodology in ethylene plant optimization based on an extended combined energy-exergy analysis', *Energy*, 164, pp. 1114-1134.

Joglekar, A. M. and May, A. T. (1987) 'Product excellence through design of experiments', *Cereal foods world*, 32(12), p. 857.

Joshi, C. and Singhal, R. S. (2016) 'Modeling and optimization of zeaxanthin production by Paracoccus zeaxanthinifaciens ATCC 21588 using hybrid genetic algorithm techniques', *Biocatalysis and Agricultural Biotechnology*, 8, pp. 228-235.

Joshi, C. and Singhal, R. S. (2018) 'Zeaxanthin production by Paracoccus zeaxanthinifaciens ATCC 21588 in a lab-scale bubble column reactor: Artificial intelligence modeling for determination of optimal operational parameters and energy requirements', *Korean Journal of Chemical Engineering*, 35(1), pp. 195-203.

Kaur, P., Ghoshal, G. and Jain, A. (2019) 'Bio-utilization of fruits and vegetables waste to produce β-carotene in solid-state fermentation: Characterization and antioxidant activity', *Process Biochemistry*, 76, pp. 155-164.

Kaur, S., Panesar, P. S., Gurumayum, S., Rasane, P. and Kumar, V. (2019) 'Optimization of aqueous extraction of orevactaene and flavanoid pigments produced by Epicoccum nigrum', *Pigment & Resin Technology.*

Kennedy, J. and Eberhart, R. (1995) 'Particle Swarm Optimization', *In Proceedings of ICNN'95-International Conference on Neural Networks,* November. IEEE, 4, pp. 1942-1948.

Kim, S. K. ed. (2013) Marine biomaterials: characterization, isolation and applications. CRC press.

Korumilli, T. and Mishra, S. (2014) 'Carotenoid production by Bacillus clausii using rice powder as the sole substrate: pigment analyzes and optimization of key production parameters', *Journal of Biochemical Technology*, 5(4), pp. 788-794.

Lopes, F. C. and Ligabue-Braun, R. (2021) 'Agro-industrial residues: eco-friendly and inexpensive substrates for microbial pigments production', *Frontiers in Sustainable Food Systems*, 5, p.65.

Lim, Y. H., Foo, H. L., Loh, T. C., Mohamad, R. and Abdul Rahim, R. (2020) 'Rapid evaluation and optimization of medium components governing tryptophan production by Pediococcus acidilactici tp-6 isolated from Malaysian food via statistical approaches', *Molecules*, 25(4), p.779.

Liu, Y., Zhou, Q., He, Y. M., Ma, X. Y., Liu, L. N. and Ke, Y. J. (2021) 'Optimization of preparation and properties of Gardenia yellow pigment-loaded alginate beads', *Korean Journal of Chemical Engineering*, pp. 1-7.

Mahmoud, G. A. E., Soltan, H. A., Abdel-Aleem, W. M. and Osman, S. A. (2021) 'Safe natural bio-pigment production by Monascus purpureus using mixed carbon sources with cytotoxicity evaluation on root tips of Allium cepa L', *Journal of Food Science and Technology*, 58(7), pp. 2516-2527.

Mehri, D., Perendeci, N. A. and Goksungur, Y. (2021) 'Utilization of whey for red pigment production by monascus purpureus in submerged fermentation', *Fermentation,* 7(2), p.75.

Menezes, B. S., Solidade, L. S., Conceição, A. A., Santos Junior, M. N., Leal, P. L., de Brito, E. S., Canuto, K. M., Mendonça, S., de Siqueira, F. G. and Marques, L. M. (2020) 'Pigment production by Fusarium solani BRM054066 and determination of antioxidant and anti-inflammatory properties', *AMB Express*, 10(1).

de Menezes, L. H. S., Carneiro, L. L., de Carvalho Tavares, I. M., Santos, P. H., das Chagas, T. P., Mendes, A. A., da Silva, E. G. P., Franco, M. and de Oliveira, J. R. (2021) 'Artificial neural network hybridized with a genetic algorithm for optimization of lipase production from Penicillium roqueforti ATCC 10110 in solid-state fermentation', *Biocatalysis and Agricultural Biotechnology*, 31, pp. 101885.

Mohamad, A. B., Zain, A. M. and Nazira Bazin, N. E. (2014) ‘Cuckoo search algorithm for optimization problems—a literature review and its applications’, *Applied Artificial Intelligence*, 28(5), pp. 419-448.

Montgomery, D. C., Peck, E. A. and Vining, G. G. (2021) *Introduction to linear regression analysis*. John Wiley & Sons.

Morales-Oyervides, L., Oliveira, J. C., Sousa-Gallagher, M. J., Méndez-Zavala, A. and Montañez, J. C. (2017) ‘Selection of best conditions of inoculum preparation for optimum performance of the pigment production process by Talaromyces spp. using the Taguchi method’, *Biotechnology Progress*, 33(3), pp. 621-632.

Mourabet, M., El Rhilassi, A., El Boujaady, H., Bennani-Ziatni, M. and Taitai, A. (2017.) ‘Use of response surface methodology for optimization of fluoride adsorption in an aqueous solution by Brushite’, *Arabian Journal of Chemistry,* 10, pp. S3292-S3302.

Nazghelichi, T., Aghbashlo, M. and Kianmehr, M. H. (2011) ‘Optimization of an artificial neural network topology using coupled response surface methodology and genetic algorithm for fluidized bed drying’, *Computers and Electronics in Agriculture*, 75(1), pp. 84-91.

Numan, M., Bashir, S., Mumtaz, R., Tayyab, S., Rehman, N. U., Khan, A. L., Shinwari, Z. K. and Al-Harrasi, A. (2018) ‘Therapeutic applications of bacterial pigments: a review of current status and future opportunities’, *Biotech*, 8(4), pp. 1-15.

Pal, M. P., Vaidya, B. K., Desai, K. M., Joshi, R. M., Nene, S. N. and Kulkarni, B. D. (2009) ‘Media optimization for biosurfactant production by Rhodococcus erythropolis MTCC 2794: artificial intelligence versus a statistical approach’, *Journal of Industrial Microbiology and Biotechnology,* 36(5), pp. 747-756.

Poorniammal, R., Gunasekaran, S. and Murugesan, R. (2015.) ‘Statistical optimization of culture medium for yellow pigment production by Thermomyces sp.’, *Journal of Applied and Natural Science,* 7(1), pp. 203-210.

Renge, V. C. and Khedkar, S. V. (2012) 'Enzyme synthesis by fermentation method: a review', *Scientific Reviews and Chemical Communications*, 2(4).

Rosa, J. M., Guerhardt, F., Júnior, S. E. R. R., Belan, P. A., Lima, G. A., Santana, J. C. C., Berssaneti, F. T., Tambourgi, E. B., Vanale, R. M. and de Araújo, S. A. (2021) ‘Modeling and optimization of reactive cotton dyeing using response surface methodology combined with artificial neural network and particle swarm techniques’, *Clean Technologies and Environmental Policy*, pp. 1-11.

Said, F. M. and Hamid, N. F. B. (2018) ‘Optimization of red pigment production by Monascus purpureus FTC 5356 using response surface methodology’, *IIUM Engineering Journal*, 19(1), pp. 34-47.

Said, F. M. and Hamid, N. F. B. (2019) ‘Natural red colorant via solid-state fermentation of oil palm frond by Monascus purpureus FTC 5356: effect of operating factors’, *Journal of Engineering Science and Technology*, 14(5), pp. 2576-2589.

Said, F. M. and Razali, M. A. A. (2019) 'Effect of factors on the red pigment production in the stirred drum bioreactor: Fractional factorial design approach', *In AIP Conference Proceeding*s. September 2019. IP Publishing LLC, 2155(1), pp. 20008.

Saini, D. K., Rai, A., Devi, A., Pabbi, S., Chhabra, D., Chang, J. S. and Shukla, P. (2021) ‘A multi-objective hybrid machine learning approach-based optimization for enhanced biomass and bioactive phycobiliproteins production in Nostoc sp. CCC-403’, *Bioresource Technology*, 329, pp. 124908.

Saini, D. K., Yadav, D., Pabbi, S., Chhabra, D. and Shukla, P. (2020) ‘Pycobiliproteins from Anabaena variabilis CCC421 and its production enhancement strategies using combinatory evolutionary algorithm approach’, *Bioresource Technology,* 309, pp. 123347.

Sarma, M. V. R. K., Sahai, V. and Bisaria, V. S. (2009) ‘Genetic algorithm-based medium optimization for enhanced production of fluorescent pseudomonad R81 and siderophore’, *Biochemical Engineering Journal,* 47(1-3), pp. 100-108.

Seyedin, A., Hatamian-Zarmi, A., Rasekh, B. and Mirderikvand, M. (2015) ‘Natural pigment production by Monascus purpureus: Bioreactor yield improvement through statistical analysis’, *Applied Food Biotechnology*, 2(2), 2 pp. 3-30.

Shair, E. F., Khor, S. Y., Abdullah, A. R., Jaafar, H. I., Saharuddin, N. Z. and Abidin, A. Z. (2015) ‘Cuckoo Search Approach for Cutting Stock Problem’, *International Journal of Information and Electronics Engineering*, 5(2), pp. 138.

Sharma, R. and Ghoshal, G. (2020) 'Optimization of carotenoids production by Rhodotorula mucilaginosa (MTCC-1403) using agro-industrial waste in bioreactor', *A statistical approach Biotechnology Reports,* 25, pp. e00407.

Sharmila, G., Muthukumaran, C., Suriya, E., Keerthana, R. M., Kamatchi, M., Kumar, N.M., Anbarasan, T. and Jeyanthi, J. (2019) 'Ultrasound aided extraction of yellow pigment from Tecoma castanifolia floral petals: Optimization by response surface method and evaluation of the antioxidant activity', *Industrial Crops and Products,* 130, pp. 467-477.

Shetty, A. V. K., Dave, N., Murugesan, G., Pai, S., Pugazhendhi, A., Varadavenkatesan, T., Vinayagam, R. and Selvaraj, R. (2021) 'Production and extraction of red pigment by solid-state fermentation of broken rice using Monascus sanguineus NFCCI 2453', B*iocatalysis and Agricultural Biotechnology*, 33, pp. 101964.

Shukla, M. and Nadumane, V. K. (2018.) 'Statistical optimization of culture conditions by response surface methodology for the enhanced production of a cytotoxic pigment from Pseudomonas stutzeri JGI 52', *Journal of Pharmacognosy and Phytochemistry,* 7(2), pp. 2159-2166.

Silbir, S. and Goksungur, Y. (2019) 'Natural red pigment production by Monascus purpureus in submerged fermentation systems using a food industry waste: Brewer's spent grain', *Foods*, 8(5), pp. 161.

Silveira, S. T., Daroit, D. J. and Brandelli, A. (2008) 'Pigment production by Monascus purpureus in grape waste using factorial design', *LWT-Food Science and Technology,* 41(1), pp. 170-174.

Singh, D., Barrow, C. J., Mathur, A. S., Tuli, D. K. and Puri, M. (2015) 'Optimization of zeaxanthin and β-carotene extraction from Chlorella saccharophila isolated from New Zealand marine waters', *Biocatalysis and Agricultural Biotechnology,* 4(2), pp. 166-173.

Singh, N., Goel, G., Singh, N., Pathak, B. K. and Kaushik, D. (2015) 'Modeling the red pigment production by Monascus purpureus MTCC 369 by Artificial Neural Network using rice water based medium', *Food Bioscience,* pp. 11, 17-22.

Singh, V., Haque, S., Niwas, R., Srivastava, A., Pasupuleti, M. and Tripathi, C. K. M. (2017). 'Strategies for fermentation medium optimization: an in-depth review', *Frontiers in Microbiology,* 7, pp. 2087

Sinha, K., Chowdhury, S., Saha, P. D. and Datta, S. (2013) 'Modeling of microwave-assisted extraction of natural dye from seeds of Bixa orellana (Annatto) using response surface methodology (RSM) and artificial neural network (ANN)', *Industrial Crops and Products*, 41, pp. 165-171.

Sinha, K., Saha, P. D. and Datta, S. (2012) 'Response surface optimization and artificial neural network modeling of microwave assisted natural dye extraction from pomegranate rind', *Industrial Crops and Products*, 37(1), pp. 408-414.

Su, W. T., Tsou, T. Y. and Liu, H. L. (2011) 'Response surface optimization of microbial prodigiosin production from Serratia marcescens', *Journal of the Taiwan Institute of Chemical Engineers*, 42(2), pp. 217-222.

Suhaimi, S. N., Hasan, S. and Mariyam, S. (2018) 'Statistical and nature-inspired metaheuristics analysis on flexirubin production', *Int. J. Advance Soft Compu. Appl*, 10(2).

Suwannarach, N., Kumla, J., Nishizaki, Y., Sugimoto, N., Meerak, J., Matsui, K. and Lumyong, S. (2019) 'Optimization and characterization of red pigment production from an endophytic fungus, Nigrospora aurantiaca CMU-ZY2045, and its potential source of natural dye for use in textile dyeing', *Applied Microbiology and Biotechnology*, 103(17), pp. 6973-6987.

Tharek, A., Yahya, A., Salleh, M. M., Jamaluddin, H., Yoshizaki, S., Dolah, R., Hara, H., Iwamoto, K. and Mohamad, S. E. (2020) 'Improvement of Astaxanthin Production in Coelastrum sp. by Optimization Using Taguchi Method' Applied *Food Biotechnology,* 7(4), pp. 205-214.

Usman, H. M., Abdulkadir, N., Gani, M. and Maiturare, H. M. (2017) 'Bacterial pigments and its significance', *MOJ Bioequiv Availab*, 4(3), pp. 00073.

Vedaraman, N., Sandhya, K. V., Charukesh, N. R. B., Venkatakrishnan, B., Haribabu, K., Sridharan, M.R. and Nagarajan, R.J.C.E. (2017) 'Ultrasonic extraction of natural dye from Rubia cordifolia, optimization using response surface methodology (RSM) & comparison with artificial neural network (ANN) model and its dyeing properties on different substrates', *Chemical Engineering and Processing: Process Intensification*, 114, pp. 46-54.

Venil, C. K., Dufossé, L. and Renuka Devi, P. (2020) 'Bacterial pigments: sustainable compounds with market potential for pharma and food industry', *Frontiers in Sustainable Food Systems,* 4, pp. 100.

Venil, C. K., Sathishkumar, P., Malathi, M., Usha, R., Jayakumar, R., Yusoff, A. R. M. and Ahmad, W. A. (2016) 'Synthesis of flexirubin-mediated silver nanoparticles using Chryseobacterium artocarpi CECT 8497 and investigation of its anticancer activity', *Materials Science and Engineering: C, 59*, pp. 228-234.

Venil C. K., Zakaria, Z. A. and Ahmad, W. A. (2013) 'Bacterial pigments and their applications', *Process Biochemistry*, 48(7), pp. 1065-1079.

Venil C. K., Zakaria, Z. A. and Ahmad, W. A. (2015) 'Optimization of culture conditions for flexirubin production by Chryseobacterium artocarpi CECT 8497 using response surface methodology', *Acta Biochimica Polonica*, pp. 62(2).

Venkatachalam, M., Shum-Chéong-Sing, A., Dufossé, L. and Fouillaud, M. (2020) 'Statistical optimization of the physico-chemical parameters for pigment production in submerged fermentation of Talaromyces albobiverticillius 30548', *Microorganisms*, pp. 8(5), 711.

Wu, J., Zhang, J., Yu, X., Shu, Y., Zhang, S. and Zhang, Y. (2021) 'Extraction optimization by using response surface methodology and purification of yellow pigment from Gardenia jasminoides var. radicans Makikno', *Food Science & Nutrition*, 9(2), pp. 822-832.

Yang, X. S. and He, X. (2013) 'Bat algorithm: literature review and applications', *International Journal of Bio-inspired computation,* 5(3), pp. 141-149.

Yang, X. S. ed., (2013) *Cuckoo search and firefly algorithm: Theory and applications.* Springer, 516.

Yang, X.S. and He, X. (2013) 'Firefly algorithm: recent advances and applications', *International Journal of Swarm Intelligence*, pp. 1(1), 36-50.

Yang, X.S. and Deb, S. (2014) 'Cuckoo search: recent advances and applications', *Neural Computing and Applications*, 24(1), pp. 169-174.

Zhu, X., Mang, Y., Shen, F., Xie, J. and Su, W. (2014) 'Homogenate extraction of gardenia yellow pigment from Gardenia Jasminoides Ellis fruit using response surface methodology', *Journal of Food Science and Technology*, 51(8), pp. 1575-1581.

LIST OF PUBLICATIONS

Indexed Journal

1. Suhaimi, S. N., Hasan, S. and Mariyam, S. (2018) ‘Statistical and nature-inspired metaheuristics analysis on flexirubin production’, *Int. J. Advance Soft Compu. Appl*, pp. 10(2). **(Indexed by Scopus)**

2. Suhaimi, S. N., Shamsuddin, S. M., Ahmad, W. A., Hasan, S. and Venil, C.K. (2019) ‘Comparison of particle swarm optimization and response surface methodology in fermentation media optimization of flexirubin production’, *Jurnal Teknologi*, 81(2). **(Indexed by Scopus)**

3. Suhaimi, S. N., Shamsuddin, S. M., Hasan, S. and Ahmad, W. A. (2018) ‘Multi-Parameters Optimization from Agricultural Waste Using Genetic Algorithm’, *Advanced Science Letters*, 24(10), pp.7507-7511**. (Web of Science)**