**Abstract**

Indigo is a natural dye that is widely used in the textile industry worldwide. However, the synthesis of indigo using toxic compounds such as aniline, formaldehyde, and hydrogen cyanide leads to environmental pollution and poses a threat to workers' health. To overcome these challenges, bio-indigo or indigo biosynthesis has been proposed to replace indigo synthesized from aniline. Among the various biosynthesis methods, Flavin-containing Monooxygenases (FMOs) have been found to achieve the highest yield (1700 mg/L) of bio-indigo. However, the commercialization of indigo biosynthesis still faces several challenges. This review explores the history of indigo biosynthesis by FMOs and identifies the expensive substrate L-tryptophan, unsuitable chassis Escherichia coli, and relatively low yield and high cost compared with the chemical method as the main reasons. Additionally, this paper summarizes the strategies to improve the yield and applications of indigo synthesized by FMOs.

**Keywords:** Flavin-containing Monooxygenase, Indigo

**Introduction**

Indigo, a naturally occurring dye derived from botanical sources, boasts a historical legacy of more than 6,000 years, with extraction methods deeply rooted in tradition. Its prominent application in the textile industry, notably in the dyeing of jeans and various fabrics, underscores its industrial significance. However, the prevailing manufacturing paradigm, yielding approximately 80,000 tonnes of indigo annually, relies extensively on non-renewable petrochemicals. This conventional approach concurrently precipitates the formation of deleterious compounds (Stasiak et al. (2014) and Linke, J.A. et al. (2023)). In response to the environmental ramifications intrinsic to such processes, the conceptualization of bio-indigo has emerged as a prospective avenue. This innovative paradigm employs synthetic biology methodologies to effectuate the synthesis of indigo from tryptophan or indole, presenting a promising trajectory towards a sustainable and environmentally benign indigo production methodology.

While numerous countries, including China, the United States, and France, host companies actively engaged in the commercialization of bio-indigo, progress has been impeded by suboptimal yields. Addressing this challenge, flavin-containing monooxygenases (FMOs) have emerged as focal points of investigation, given their demonstrated capability to synthesize bio-indigo. Notably, FMOs have become the subject of extensive research over the past decades, positioning them as one of the pivotal enzymatic entities in endeavors to overcome the limitations associated with bio-indigo production.

Flavin-containing monooxygenase (FMO, EC 1.14.13.8), classified as a member of the class B flavoprotein monooxygenases (FPMOs), is encoded by a singular gene and features a tightly bound flavin adenine dinucleotide (FAD) cofactor. Recent investigations have brought to light a comprehensive indigo-catalytic model of FMOs, as detailed by Ziegler in 1993 (Fig. 4E). The catalytic process unfolds in five discrete stages: (1) the NADPH-driven reduction of FAD to FADH2, accompanied by an additional H+; (2) the interaction of FADH2 with O2, yielding a stable C4a-(hydro)peroxide intermediate; (3) the substrate undergoes unassisted oxidation without specific binding; (4) release of the residual oxygen atom as H2O; and (5) the entire cycle resets to the initial state upon the dissociation of NADP+ from FMO.

**1. The Research History of Indigo Biosynthesis by FMOs**

In the quest for indigo biosynthesis, exploration into microbial synthesis pathways has been proposed. Engineered *Escherichia coli* (*E. coli*) has notably demonstrated its efficacy as a viable platform for indigo biosynthesis, as evidenced by seminal studies (Ensley et al., 1983; Murdock et al., 1993; Berry et al., 2002; Doukyu et al., 2003). Throughout the research discussed in this chapter, *E. coli* predominantly serves as the chosen chassis for investigating indigo synthesis pathways.

Following the oxidation of indole to indoxyl, the subsequent spontaneous dimerization of two indoxyl molecules, accompanied by a reaction with oxygen, results in the formation of indigo. Consequently, a pivotal aspect in the biosynthesis of indigo revolves around the judicious selection of an appropriate oxidase to catalyze the conversion of indole to indoxyl. Therefore, this review will explore the history of indigo biosynthesis in the order of the utilization of different oxidases in this transformative process.

**1.1 Early Research on Indigo Biosynthesis**

The earliest record of indigo biosynthesis arises from the study of naphthalene dioxygenases (NDO) form *Pseudomonas putida* PpG7. In 1983, Ensley pioneered the construction of the initial synthetic indigo-producing Escherichia coli (E. coli) strain by introducing NDO, yielding an indigo production of 25 mg/L. Notably, native *E. coli* tryptophanase (TRP/TnaA) was utilized to convert L-tryptophan to indole, subsequently catalyzed by NDO to form indigo (Ensley et al., 1983). Building upon this foundation, Ensley and colleagues further explored NDO expression by employing various plasmids and inducers in 1988, providing crucial insights for subsequent investigations. The construction of the pBS959 plasmid in 1989, based on the nahA gene (NDO expressing gene) and pUC19 vector, marked a milestone in realizing indigo synthesis within recombinant E. coli (Boronin et al., 1989). However, the initial expression levels of indigo in recombinant *E. coli* was much lower compared to *Pseudomonas putida*.

In 1993, Murdock et al. enhanced indigo production by incorporating a lac promoter and operator into the plasmid, approaching expression levels comparable to *Pseudomonas putida*, resulting in a yield of 135 mg/L—a notable 5.4-fold increase. The engineered E. coli strain also demonstrated the capacity to produce indigo from glucose by inactivating the trpB gene. Nevertheless, a feedback effect was identified during the formation of 3-deoxy-D-arabino-heptulosonate 7-phosphate (DAHP), indicating the downstream product indigo could inhibit DAHP formation. To overcome this challenge, Berry et al. in 2002 achieved a 60% increase in indigo production by engineering a feedback-resistant DAHP synthase (Berry et al., 2002).

Research extended to explore NDO from different species. In 2010, NDO from *Pseudomonas sp.* HOB1 demonstrated the capability to transform 0.3 mM indole in 8 hours, yielding an impressive indigo production of 246 mg/L (Pathak and Madamwar, 2010). Subsequently, Qu et al. conducted a study in 2012 utilizing an indigo-producing strain named *Comamonas sp.* MQ, which, with the consumption of 0.05 g/L indole and 0.2 g/L naphthalene, produced 32.2 mg/L of indigo (Qu et al., 2012b).

Another extensively explored oxidase for indigo synthesis is toluene dioxygenases. In 1989, Stephens et al. integrated a toluene dioxygenase from *Pseudomonas putida* NCIB 11767 into *E. coli* HB101 using pIG, achieving the synthesis of approximately 60 mg/L of indigo through the supplementation of 5 mM tryptophan (Stephens et al., 1989).

Some recombinant *E. coli* systems for indigo synthesis have been constructed based on multicomponent phenol hydroxylases. From *Acinetobacter sp.* ST-550, Doukyu et al. identified a functional enzyme akin to multicomponent phenol hydroxylases, demonstrating the capacity for indigo synthesis. In 2002, they assessed the performance of *Acinetobacter sp.* ST-550 cultured with 10% diphenylmethane and 0.9 mg/ml indole, resulting in an indigo production of 292 mg/L (Doukyu et al., 2002). Subsequently, in 2003, they engineered the recombinant *E. coli* strain OST3410 with this functional enzyme, yielding a production of 52.1±1.6 mg/L of indigo under the conditions of 10% diphenylmethane and 0.9 mg/ml indole (Doukyu et al., 2003). In 2012, Qu et al. identified a multicomponent phenol hydroxylase from *Arthrobacter sp.* W1 (PHw1), including the measurement of its kinetic parameters to indole (Qu et al., 2012a).

However, it is crucial to note that the practical applications of multicomponent enzymes are constrained by their fermentation conditions. The yield of indigo synthesized by these enzymes has not surpassed 300 mg/L due to the requisite stability of each component under specific conditions, rendering flavin-containing monooxygenases (FMOs) with simpler components more operationally practical.

Moreover, evidence suggests that class D flavoprotein monooxygenases, closely related to FMOs, are capable of synthesizing indigo. Notably, an indole oxygenase (indAB) was identified in *Cupriavidus sp.* SHE has demonstrated the ability to synthesize indigo, achieving a production level of 307 mg/L with the provision of 1.0 g/L tryptophan (Dai et al., 2019). However, further research is needed to elucidate the underlying biosynthetic mechanisms at play in this process.

**1.2 Indigo Biosynthesis by Bacterial FMO**

Researchers aspire to enhance bio-yield and simplify production conditions, with current emphasis on Flavin-containing monooxygenase (FMO) standing out prominently in these endeavors. Bacterial FMO, also referred to as trimethylamine monooxygenase (TMM), exhibits a versatile substrate profile, encompassing the oxidation of various nitrogen and sulfur-containing compounds. Notably, it can catalyze the oxidation of indole, trimethylamine (TMA), dimethylsulfate (DMS), and dimethylsulfoxide (DMSO) (Chen et al., 2011; Choi et al., 2003).

Of great significance is understanding the mechanism by which FMOs contribute to indigo synthesis. In bacterial systems, tryptophan is initially converted to indole by tryptophanase (TRP), and subsequently, FMOs oxidize indole to form either 2-hydroxyindole or 3-hydroxyindole. These intermediates are further oxidized to indoxyl by oxygen. The indoxyls subsequently undergo dimerization, yielding either indigo or indirubin (Fig. 5C). This intricate process underscores the pivotal role of FMOs in the biosynthesis of indigo.

**1.2.1 Bio-indigo Synthesis with mFMO**

The first bacterial FMO employed in engineered *Escherichia coli* for indigo production was *Methylophaga aminisulfidivorans* MPT (mFMO/bFMO). This enzyme was introduced into *E. coli* DH5α via the pBlue 2.0 vector. Following a 12-hour fermentation period supplemented with 2.00 g/L tryptophan, the recombinant E. coli successfully generated 160 mg/L of indigo (Choi et al., 2003). The kinetic parameters of mFMO to indole were measured by Alfieri et al. in 2008 (Alfieri et al., 2008). In 2019, Lončar et al. conducted a re-analysis of the kinetic parameters of wild-type mFMO catalyzing indole (Lončar et al., 2019b).

Nevertheless, the productivity of the original plasmid harboring mFMO exhibited limitations, prompting the implementation of optimization strategies. Through the removal of redundant sequences, the enhanced plasmid demonstrated a significant improvement in indigo yield, reaching 662 mg/L—a remarkable increase of 413% compared to the original production level of 160 mg/L (Han et al., 2008). Subsequently, through culture optimization with the method of response surface methodology (RSM), a notable milestone was achieved with a yield of 920 mg/L in a 5L fermenter. Further advancements led to the development of a larger-scale fermentation system, culminating in an impressive yield of 911 ± 22 mg/L of indigo in a 3,000 L/batch setup, with an input of 2 g/L of tryptophan (Han et al., 2011). Han et al. also reported a continuous fermentation conducted in a 5L system supplied with 3 g/L tryptophan, in which 23 g of indigo was produced for 110 hours, at a rate of 11.3 mg/L/h (Han et al., 2011).

The redox reaction of the tightly linked flavin adenine dinucleotide (FAD) cofactor, intrinsic to flavin-containing monooxygenases (FMO), is contingent upon the assistance of nicotinamide adenine dinucleotide phosphate (NADPH) (Alfieri et al., 2008; Eswaramoorthy et al., 2006; Krueger and Williams, 2005). However, in extracellular enzyme reaction systems or recombinant cells, the rate of NADPH regeneration may constrain the overall reaction rate. To address this, an optimized strategy involved the fusion of mFMO and phosphate dehydrogenase (PTDH), exploiting phosphate as a cost-effective and sacrificial substrate (Rioz-Martinez et al., 2011). The researchers further examined the catalytic efficiency of purified PTDH-mFMO and cell-free extract (CFE), discovering that the purified enzyme exhibited superior performance, yielding 300 mg/L of indigo when supplied with 10 mM indole (Lončar et al., 2019b).

Furthermore, directed evolution was employed to modify mFMO, utilizing a computational library design protocol named FRESCO, a structure-based enzyme engineering tool for stabilization (Wijma et al., 2018). FRESCO was leveraged to enhance mFMO's thermostability. Lončar et al. conducted screening for site-directed mutants and multichange isothermal mutagenesis (MISO) mutants. Some of these mutants exhibited an increase in the apparent melting temperature (Tm) by 3 °C, while others demonstrated enhanced catalytic performance on indole (Lončar et al., 2019b). Notably, in 2022, the catalytic efficiency of mFMO was improved by 6.6-fold through the application of FRESCO (Sun et al., 2022).

Additionally, the enzyme tryptophanase (TRP) can convert tryptophan into indole and pyruvate (Shimada et al., 2004). Given that pyruvate can serve as a substrate for the generation of NADPH within the cell, a comprehensive integration of earlier research on yield improvement, including sequence optimization, led to the development of a bifunctional fusion enzyme, mFMO-TRP. This novel approach enabled the efficient conversion of 2.0 g of tryptophan into 1.7 g of indigo per liter of culture, representing the highest amount ever reported in the literature (Fabara and Fraaije, 2020). In 2023, utilizing TnaA, a TRP from E. coli K12, Ham et al. achieved indigo production of 1.08 g/L when supplied with 10 mM tryptophan (Ham et al., 2023).

Methods for indigo production using glucose as a substrate have been developed, as researched by Murdock et al., and later applied by Du et al. (Du et al., 2018). Chen et al. further investigated and enhanced this process by introducing a novel approach involving the use of 5 g/L glycerol as a substrate for indigo production. This modification resulted in a production yield of 104.3 mg/L, surpassing the performance achieved using glucose alone (Chen et al., 2021).

Rioz-Martinez et al. illustrated the efficacy of mFMO-PTDH by catalyzing the oxidation of indole and indole thioanisole derivatives, resulting in the synthesis of a diverse array of indigo compounds, each manifesting distinctive colors (Rioz-Martinez et al., 2011). Notably, mFMO-PTDH exhibited the capability to synthesize modified indigo, including halogenated indigo variants (Schnepel et al., 2021). This bifunctional enzyme, mFMO-PTDH, not only showcases proficiency in oxidizing indole and its analogs but also demonstrates potential in chirality selection, particularly in the biocatalytic sulfoxide oxidation of prochiral sulfides (Pereira et al., 2022; Wojaczyńska and Wojaczyński, 2020). A consecutive two-cell reaction system was devised for the synthesis of dichloro-indigo, a halogenated variant of indigo, starting from tryptophan.

Indigo's intrinsic insolubility in water necessitates the addition of reductants, such as sodium sulfate, to transform it into a water-soluble dye during practical production. However, this conventional approach brings about economic and environmental burdens. To overcome the insolubility challenge of indigo in water, a novel strategy involving chemical group protection has been proposed. This innovative method entails the co-expression of a glycosyltransferase from Polygonum tinctorium with mFMO in Escherichia coli. This co-expression introduces a glucose group to protect the active hydroxyl group of hydroxyindole, resulting in the creation of a water-soluble and stable pigment named indican (Hsu et al., 2018). Through fed-batch fermentation, the recombinant E. coli strain TMH011 successfully produced 2.9 g/L of indican. Given that two indoxyl molecules are required to produce one indigo molecule, the fermentation result can be converted to 1.4 g/L of indigo production. This approach offers a promising solution to enhance the environmental sustainability and economic viability of indigo synthesis.

Indirubin, an indole alkaloid with applications as a drug in chronic myeloid leukemia, has exhibited anticancer effects (Yang et al., 2022). Traditional production methods have relied on plant cell culture extraction. However, with the utilization of the improved mFMO (Han et al., 2008), the biosynthetic pathway of indirubin has been further explored. Cysteine was identified to enhance the selectivity of FMO for 2-hydroxyindole (Han et al., 2013), resulting in a yield of 223.6 mg/L under optimized conditions. In a fed-batch fermentation conducted by Du et al., mFMO and *Escherichia coli* tryptophanase (TRP) were employed to biologically synthesize indirubin using glucose as the primary substrate. This system yielded 56 mg/L of indirubin and 640 mg/L of indigo with a fed glucose concentration of 5.4 g/L (Du et al., 2018). Subsequent studies revealed that cysteine significantly influenced the catalytic selectivity of mFMO. As the concentration of cysteine increased during the oxidation catalytic process, the reaction tended towards indirubin synthesis (Kim et al., 2019), holding considerable significance for the synthesis of indirubin by mFMO. In 2022, a semi-rational design, combined with modifications in two regions (K223R/D317S) of FMO, was applied. Through metabolic engineering technology, E. coli strains were screened to achieve high indirubin production, reaching the current maximum yield of 860.7 mg/L (Sun et al., 2022).

The bio-production of indigo can be extended by co-culturing with other materials to achieve in vitro coloration. In 2023, Cho et al. demonstrated the simultaneous production of polyhydroxybutyrate (PHB) film and isobutanol in *E. coli* BL21(DE3) along with indigo catalyzed by mFMO. This innovative approach yielded 1.1 mg of indigo per gram of PHB content (Cho et al., 2023a) and 194.1 mg/L of indigo with the production of 5.8 g/L of isobutanol (Cho et al., 2023b). This research showcases the potential for versatile applications of indigo bio-production in combination with other materials.

**1.2.2 Bio-indigo Synthesis with other FMOs**

In addition to mFMO, researchers have explored other flavin-containing monooxygenases (FMOs) for indigo synthesis.

In 2015, Ameria et al. discovered an FMO from *Corynebacterium glutamicum* (cFMO) and cloned it into *E. coli* WCO21 using pMCF14. After 48 hours of fermentation with a supplementation of 2.50 g/L tryptophan, the system produced 685 mg/L of indigo and 103 mg/L of indirubin (Ameria et al., 2015). Subsequently, Jung et al. investigated cFMO through site-directed mutagenesis. The mutant with T326S was cloned into E. coli WTS326, resulting in a production of 1040 mg/L of indigo and 112 mg/L of indirubin (Jung et al., 2018).

In 2019, Lončar et al. identified a new FMO from *Nitrincola lacisaponensis* (NiFMO), which exhibited an optimum catalytic temperature of 51 °C. Sequence alignment indicated that NiFMO shares 74% sequence identity with mFMO. In 2021, Inoue et al. cloned the FMO from *Polygonum tinctorium* (PtFMO), a plant from which indigo is naturally extracted. The recombinant *E. coli* demonstrated the capability to produce indigo, yielding 30 mg/L in 24 hours (Lončar et al., 2019; Inoue et al., 2021).

**2. The Difference between Synthetic Technologies**

This chapter will review the differences among synthetic technologies. Initially, we will delve into the technologies employed in crafting the biosynthetic system, beginning with the genetic modification of the host cell's metabolic pathway in the upstream process, extending to fermentation in various scales and under diverse fermentation conditions in the downstream. Subsequently, we will compare different research methodologies, starting with enzyme purification and culminating in the assessment of indigo fermentation rates.

**2.1 Technologies Applied to Construct the Biosynthetic System of Indigo**

**2.1.1 Genetic Modification of the Host Cell’s Metabolic Pathway**

The main aim of modification of the host cell is to make the recombinant cell produce indigo in a more appropriate reaction environment. In the concern of producing cost, the trpB gene was inactivated to validate the expression of indigo from glucose. This modification can be adapted to other applications of indigo synthesis. Like synthesis with the help of FMOs, as the research before was conducted with the oxidase of naphthalene dioxygenases (NDO), this system can be used to FMO directly, as the engineering of host cell was to block the transfer of indole to tryptophan in the process of tryptophan biosynthesis, indole will be accumulated in the cell. The accumulation of indole has toxicity to the host cell. Once the catalytic rate is lower than the accumulation rate, the accumulation of indole will drive toxicity to the host cell. Therefore, to prevent the effect, an acceleration of enzyme catalyzing is important to the expression system. The first step of the aromatic acids biosynthesis is the formation of 3-deoxy- D-arabino-heptulosonate 7-phosphate. However, the final product indigo will inactivate the synthase which displays a feedback effect. Engineering the synthase to a feedback-resistant type will make the catalytic process higher activity. of enzyme catalyzing. kinetic parameters. and figure out the problem of indole accumulation.

**2.1.2 The Optimization of Enzyme Encoding Gene**

**3. The Substrates of Indigo Biosynthesis by FMOs**

Over the past four decades, researchers have dedicated significant efforts to the study of substrates involved in the biosynthesis of indigo. Their endeavors have been focused on gaining a profound understanding of the mechanisms of enzymes and the intricate reaction pathways associated with different substrates. Leveraging cutting-edge technologies, researchers have employed genetic modification strategies, manipulating microbial hosts such as *Escherichia coli*. Additionally, through optimizing the genes encoding crucial enzymes in the synthesis pathway, researchers have sought to fine-tune the activity of these enzymes, exploring the use of various plasmids and promoters to achieve the highest conversion rates for the selected substrates.

It should be mentioned that indole has toxicity to the host microorganism.

**2.1 The Kinetic Properties of Different FMOs to indole**

The kinetic parameters show the properties that FMOs have in the catalysis of indole to indigo. Showing this will help the researchers in the future to compare the differences and make the choice of the FMO they would further study to create more productive strains helping indigo fermentation.

The kinetic parameter was investigated by --- and the result showed different site-directed mutants and multiple-site mutants have the property to catalyze. The range also showed a trend of lower kcat getting lower Km.

**Table 1.** The kcat and Km of different FMO subtypes on various substrates

In the biosynthetic strategy, indole is used as a substrate or intermediate in the pathway. With the help of heterologous FMO, indole is oxidized to 3-hydroxyindole (indophenol`/hydroxyindole), which further forms indigo by spontaneous dimerization under aerobic conditions (Choi, 2020; Han et al., 2008).

**2.2 Using Tryptophan as Substrate**

The discovery of using tryptophan as the substrate of indigo synthesis in microbes, especially in E. coli. As there is a native TRP named TnaA existing in E. coli, in 1983, when the biosynthesis of indigo was first found in Pseudomonas putida PpG7, researchers also found that, by adding 10 mM tryptophan or 1 mM indole, the production of indigo was enhanced. Sooner research proved the detrimental impact of indole toxicity on indigo production in microorganisms (Murdock et al., 1993; O'Connor et al., 1997), another alternative substrate – tryptophan was paid much attention to being the suitable substrate for indigo synthesis.

The mechanism of indigo synthesis from tryptophan was investigated. The process includes the automatic transformation of indole to tryptophan and the reaction catalyzed by TRP that will transfer tryptophan to indole and pyruvate. Some of the reaction

Through the research of Stephens et al.,