Green Molecular Transformation in Dual Catalysis: Photoredox Activation of Vitamin B_12 Using Heterogeneous Photocatalyst

Shichijo, Keita
Department of Chemistry and Biochemistry, Graduate School of Engineering Kyushu University

Shimakoshi, Hisashi
Department of Chemistry and Biochemistry, Graduate School of Engineering Kyushu University

出版情報：ChemPlusChem. 89 (6), pp.e202400041-, 2024-03-12. Wiley
バージョン：

CONCEPT

Green Molecular Transformation in Dual Catalysis: Photoredox Activation of Vitamin B_{12} Using Heterogeneous Photocatalyst

Keita Shichijo,[a] Hisashi Shimakoshi*[a]

[a] Dr. K. Shichijo, Prof. H. Shimakoshi
Department of Chemistry and Biochemistry, Graduate School of Engineering
Kyushu University
Nishi-ku, Motooka, Fukuoka, 744, 819-0395, Japan.
E-mail: shimakoshi@mail.cstm.kyushu-u.ac.jp

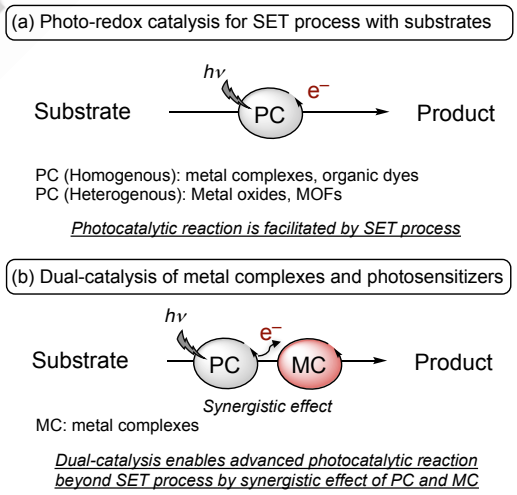
Abstract: This concept focuses on dual-catalysis using metal complexes and heterogeneous photocatalysts. Vitamin B_{12} derivatives are sophisticated metal complexes that facilitate enzymatic reactions in the biological systems. The B_{12} enzymes inspired reactions catalytically proceed in dual-catalyst systems of B_{12} derivatives and heterogeneous photocatalysts, such as titanium oxide (TiO_2) and metal-organic frameworks (MOFs), under light irradiation. The cobalt ions in vitamin B_{12} derivatives are effectively reduced by photoexcited photocatalysts, producing low-valent Co(I) species. The photoinduced nucleophilic Co(I) species react with an alkyl halide to form an organometallic complex with a Co-C bond. The Co-C bond dissociates during photolysis to generate alkyl radicals. Based on this mechanism, dual-catalysis effectively promotes various light-driven organic syntheses and light-driven dehalogenation reactions of toxic alkyl halides. The concepts of the dual-catalyst system and recent progress in this field are discussed in this concept.

1. Introduction

Although the development of the chemical industry has enriched our lives, problems such as global warming and soil pollution accelerate annually. The development of “Green and Sustainable Chemistry” is necessary to solve these problems and to realize a sustainable society.[1–3] According to the 12 principles of Green Chemistry developed by Anastas and Warner in 1998, organic synthesis that minimizes the use of chemical reagents and utilizes alternative energy sources has had a significant impact on the development of Green and Sustainable Chemistry.[4] Thus, trends in the development of green and sustainable processes over the past 25 years have focused on the use of minimal chemical reagents and alternative energy sources.

Photochemical molecular transformations are valuable in synthetic chemistry. They generate products that cannot be obtained under mild conditions. They can also synthesize fine chemicals using sunlight as a renewable energy source. Photoredox catalysis has recently received attention for photocatalytic molecular transformations (Scheme 1 a).[5,6] Photoredox catalysis relies on the capability of metal complexes and organic dyes to facilitate single-electron transfer (SET) with organic substrates upon light irradiation. Heterogeneous photocatalysts, such as metal oxides: semiconductor photocatalysts and metal-organic frameworks (MOFs): photoredox-active compounds, have also attracted attention in light-induced organic synthesis (Scheme 1 a).[7–12] This photocatalytic ability is based on the electron-hole pairs produced by light irradiation, which engage in the SET process with the organic substrate. Semiconductor photocatalysts are more useful than homogeneous photoredox catalysts because of their stability and recyclability.

Dual-catalysis by metal complexes and photosensitizers leads to interesting synergies in their catalytic properties (Scheme 1 b).[13,14] In these dual-catalyst systems, the photosensitizers absorb light and activate the metal complexes. The activated metal complexes are then reacted with the substrate. This enables advanced photocatalytic molecular transformations beyond general photocatalytic reactions using the SET process. Thus, dual-catalyst systems consisting of metal complexes and photosensitizers enable a variety of advanced molecular transformations in a green and sustainable manner.



Scheme 1. Photochemically molecular transformation; (a) photo-redox catalysis for SET process with substrates, (b) Dual-catalysis of metal complexes and photosensitizers.

As the metal complexes, cobalt complexes are excellent materials, and vitamin B_{12} is a particularly noteworthy cobalt complex.[15–17] The dual-catalysis of B_{12} derivatives and both homogeneous[18–25] and heterogeneous[26–31] photosensitizers enables the production of nucleophilic Co(I) species due to electron transfer from the photosensitizers to the B_{12} derivatives under light irradiation. The photoinduced nucleophilic Co(I) species reacts with an

electrophile, such as an alkyl halide, producing an organometallic complex with a cobalt-carbon (Co-C) bond. The Co-C bond dissociates during photolysis to generate an alkyl radical intermediate. Based on this interesting synergy, dual-catalysis effectively promotes various light-driven molecular transformations such as environmental purification and organic synthesis. Thus, the purpose of this concept is to outline the trend of a dual-catalyst system consisting of B_{12} derivatives and photosensitizers. This concept specifically focuses on heterogeneous dual-catalyst systems.

2. Vitamin B_{12} Derivatives

Naturally occurring B_{12} derivatives such as cyanocobalamin (vitamin B_{12}), methylcobalamin, and adenosylcobalamin are among the most sophisticated cofactors in living organisms (Figure 1 a). Vitamin B_{12} derivatives catalyze various molecular transformations in biological systems, including methyl group transfer, 1,2-rearrangements, DNA biosynthesis, and dehalogenation (Scheme 2). These reactivities of the vitamin B_{12} derivatives have attracted attention in the field of biological chemistry as well as organic chemistry and catalytic chemistry.[32–40] Vitamin B_{12} derivatives consist of Co ions coordinated to a monoanionic tetrapyrrole ring (corrin ring).[40] The monoanionic corrin ring stabilizes the low-valent Co(I) species. Thus, vitamin B_{12} derivatives efficiently generated nucleophilic Co(I) species. Hydrophobic derivatives of vitamin B_{12} and heptamethyl cobesters (Figure 1 b), which are soluble in common organic solvents, have been synthesized from naturally occurring vitamin

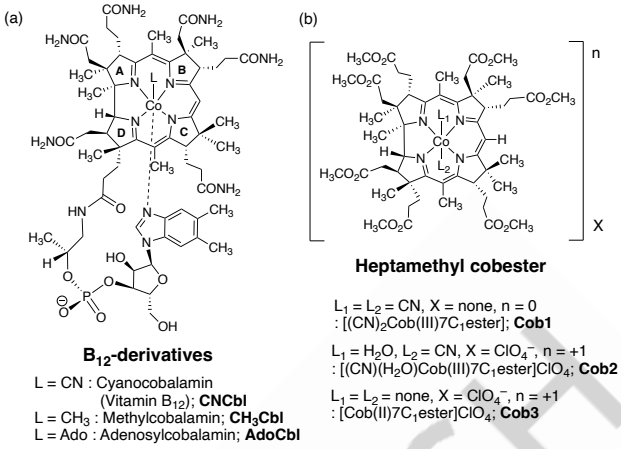
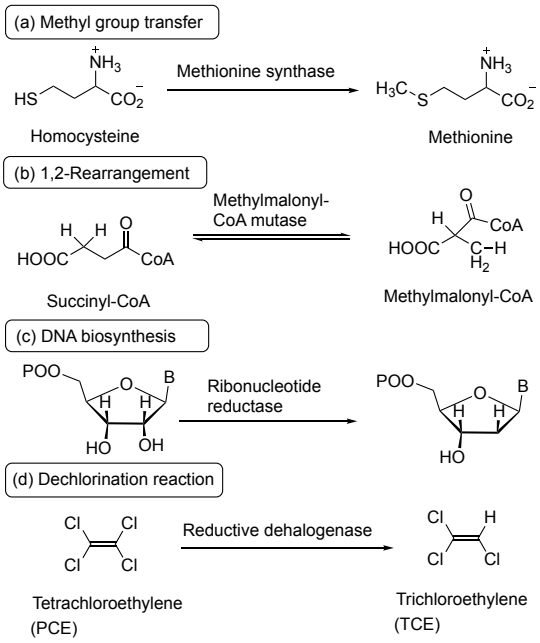


Figure 1. Structures of (a) B_{12} derivatives, (b) heptamethyl cobester.

B_{12} derivatives and extended the application of vitamin B_{12} catalysis. This heptamethyl cobester also contains a monoanionic corrin ring, which explains the efficient generation of low-valent Co(I) species. This nucleophilic Co(I) species has been used to initiate various organic syntheses and enzymatic reactions.

The specific catalytic cycle of the vitamin B_{12} derivatives is shown in Figure 2. Vitamin B_{12} derivatives contain cobalt ions in their +3 or +2-oxidation state. When the Co(II) ion is reduced in a reducing environment, the Co(I) state of vitamin B_{12} derivatives is generated with a highly nucleophilic character.[15,17] The nucleophilic Co(I) species reacts with an electrophile such as an alkyl halide, producing an organometallic complex with a Co-C bond. This Co-C bond dissociates under controlled conditions such as photolysis, electrolysis, and thermolysis to generate alkyl radical species. Bond dissociation energy of methylated complex (Co-CH_3) is determined to be 37 kcal/mol, indicating that the Co-C is a weak bond. In the case of photolysis, Co-CH_3 complex is excited at 400 nm, prompting Co−C bond homolysis with 25%



Scheme 2. B_{12} dependent enzymatic reactions; (a) methyl group transfer, (b) 1,2-rearrangement, (c) DNA biosynthesis, and (d) dichlorination reaction.

Keita Shichijo is an assistant professor in Osaka University (Japan) from 2024. He got his M.S. degree in 2021 and Ph.D. in 2024 from Kyushu University under supervision of Prof. Hisashi Shimakoshi. He worked on his Ph.D. at Kyushu University as a research fellow (DC1) from the Japan Society for the Promotion of Science. He was awarded JSCC Student Lecture Award (2023), JPA Best Presentation Award (2023), and CSJ Student Presentation Award (2022). His research interests focus on metal complexes and photocatalysts.

Hisashi Shimakoshi is a Professor of Applied Chemistry at Kyushu University (Japan). He graduated from Doshisha University (Japan) in 1993 and got his Ph.D. from Kyushu University in 2001. He was awarded the 2006 Lecture Prize for Young Scientist and the 2010 BCSJ Prize from The Chemical Society of Japan. His current interests are the development of a bioinspired catalyst with metal enzyme functions and its application to green molecular transformations.

efficiency (75% is attributed to a metastable Co(III) products). At 520 nm, it promotes homolysis of Co-C bond to form Co(II) and CH_3• radical pairs (14%).[37] Using this characteristic reactivity, various organic syntheses involving alkyl radicals have been established[41–47]. For example, the B_{12}-catalyzed Giese-type acylation of activated olefins (Scheme 3 a),[41] Giese-type reactions with alkyl tosylates (Scheme 3 b),[44] polarity reversal type of strain-release reactions (Scheme 3 c),[42] and cross-electrophile coupling of epoxides with aryl halides (Scheme 3 d)[45] have been reported in the past decade. A B_{12}-catalyzed atom-transfer radical polymerization was also reported in 2023 (Scheme 3 e).[47]

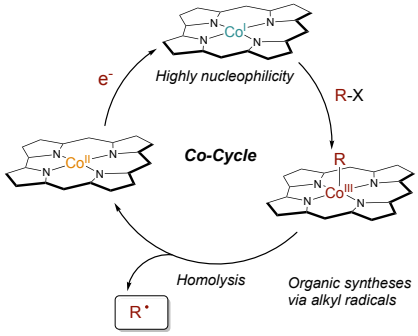


Figure 2. Cobalt cycle of vitamin B_{12} derivatives.

These reactions are fascinating bioinspired organic syntheses mediated by B_{12} derivatives. However, these reactions require chemical reductants to produce the nucleophilic Co(I) species. To achieve greener and more sustainable organic synthesis, the dual-catalysis of vitamin B_{12} derivatives and photosensitizers, such as semiconductor photocatalysts[26–31] (Figure 3 a) and photoredox catalysts[18–25] (Figure 3 b), has been developed in recent years. Photoexcited photosensitizers efficiently reduce the central cobalt to provide Co(I) species. This indicates that the characteristic reactivity of the B_{12} derivatives was induced by light irradiation. The significant advantages of the dual-catalyst system include reduction in the amount of chemical waste using a clean and renewable energy source. To date, heterogeneous dual-catalyst systems using photocatalysts, such as titanium oxide (TiO_2) and MOFs, combined with B_{12} derivatives have achieved light-driven molecular transformations. In addition, heterogeneous dual-catalysts have several advantages, including stability for recycling, accountability for removal from solution, and versatility in adding co-catalysts. Therefore, this concept summarizes the development and advantages of heterogeneous dual-catalysis.

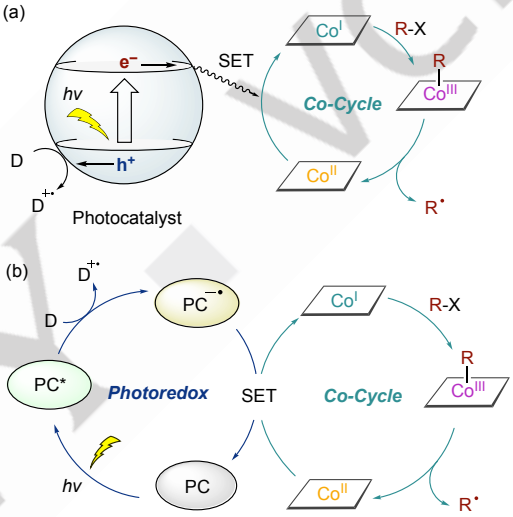
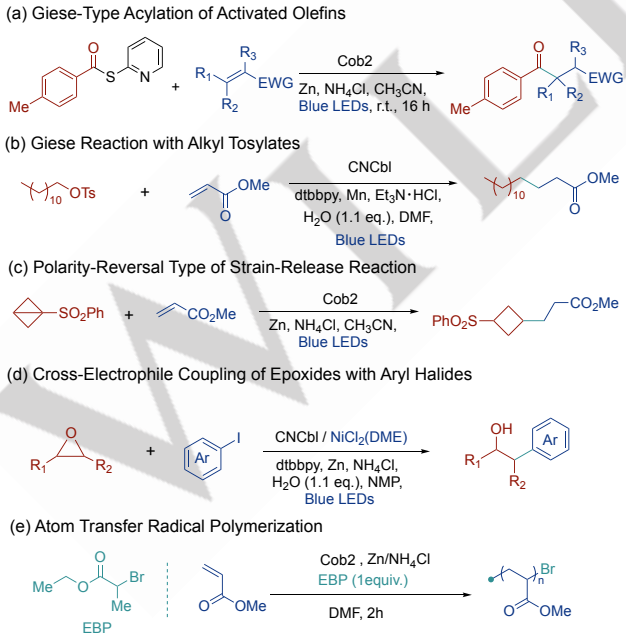


Figure 3. Dual-catalysis of vitamin B_{12} derivatives and photosensitizers; (a) B_{12} derivatives and semiconductor photocatalysts, (b) B_{12} derivatives and photo-redox catalysts. D: electron donor.



Scheme 3. B_{12} enzymes inspired organic synthetic reactions; (a) Giese-type acylation of activated olefins, (b) Giese reaction with alkyl tosylates, (c) polarity-reversal type of strain release reaction, (d) cross-electrophile coupling of epoxides with aryl halides, (e) atom transfer radical polymerization.

3. B_{12}–Dual Catalyst System

3-1. Titanium Oxide–B_{12} System (B_{12}–TiO_2)

The first heterogeneous dual-catalyst system was developed using TiO_2 as a photosensitizer (Figure 4). TiO_2 particles are known to generate electron–hole pairs under bandgap excitation with UV light irradiation (eq. 1).[48–56]

$$TiO_2 + h\upsilon \rightarrow h_{VB}{}^{+} + e_{CB}{}^{-} \quad (1)$$

The conduction band electrons (e_{CB}^-) of anatase TiO_2 shows an $E_{C.B.}$ at –0.5 V *vs.* NHE in aqueous media at pH 7. The redox potential for the Co(II/I) couple of the cobester is observed to be –0.30 V to –0.40 V *vs.* NHE in various medias. Thus, it is possible to generate Co(I) species using e_{CB}^- produced by UV irradiation of TiO_2 (Figure 4).[27–30]

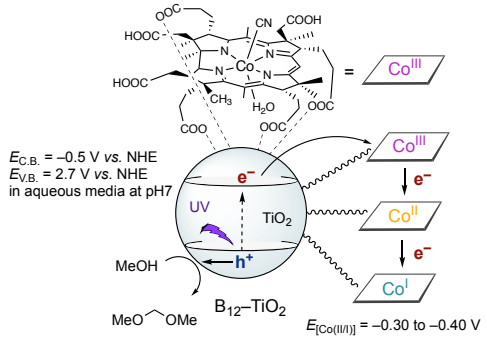
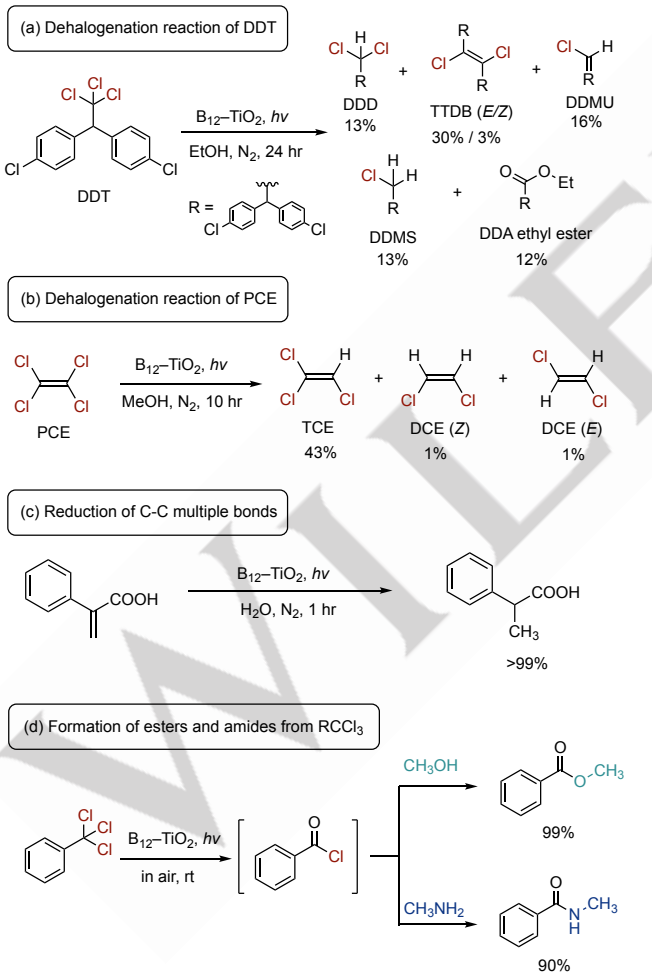


Figure 4. Electron transfer mechanism of B_{12}–TiO_2 in MeOH under UV irradiation.

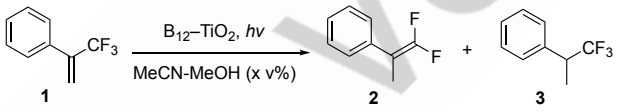
B_{12}–TiO_2 has been used for the UV-light-driven dehalogenation of toxic alkyl halides. For instance, bis(4-chlorophenyl)-2,2,2-trichloroethane (DDT) was successfully dehalogenated under mild conditions using a B_{12}–TiO_2 catalyst (Scheme 4 a).[27] PCE was also dehalogenated to TCE or DCE, catalyzed by B_{12}–TiO_2 under UV light irradiation (Scheme 4 b).[29] Light-driven organic synthesis facilitated by B_{12}–TiO_2 has also made remarkable progress in the past decade. Examples include the reduction of C-C multiple bonds (Scheme 4 c)[30] and an esterification or an amidation of trichloromethyl compounds ($RCCl_3$s) (Scheme 4 d).[31] Therefore, the recent developments in B_{12}–TiO_2 chemistry are reviewed in this section.



Scheme 4. Light-driven molecular transformation by B_{12}–TiO_2; (a) Dehalogenation reaction of DDT, (b) Dehalogenation reaction of PCE, (c) Reduction of C-C multiple bonds, (d) Esters and amide formations from $RCCl_3$.

Photocatalytic alkene reduction using B_{12}–TiO_2 coupled with C-F bond cleavage for gem-difluoroolefin synthesis was developed as a green organic synthesis method. In the reduction of multiple C-C bonds by B_{12}–TiO_2 (Scheme 4 c), the cobalt-hydrogen complex (Co-H complex) was assumed to be the intermediate, and the Co-H complex showed high reactivity for the reduction of conjugated alkenes, such as styrene derivatives and alkyl acrylates. Tian *et al.*, have found that *α*-trifluoromethyl styrene (1) having a trifluoromethyl (CF_3) group on the C=C bond converted to *gem*-difluoroolefin via C–F bond cleavage in the CF_3 group.[57]

Table 1. Photocatalytic reduction of *α*-trifluoromethylstyrene (**1**) under UV light irradiation.[a]



entry	catalyst	solvent	conv. /%	yield of **2**/%	yield of **3**/%	ratio **2**/**3**
1	B_{12}–TiO_2	MeOH	>99	29	70	0.41
2[b]	B_{12}–TiO_2	MeCN+MeOH (2.3 v%)	72	57	15	3.8
3[b]	B_{12}–TiO_2	MeCN+MeOH (17 v%)	91	65	24	2.7
4[b]	B_{12}–TiO_2	MeCN+MeOH (23 v%)	95	52	32	1.6

[a]UV irradiation (black light, λ_{max} = 365 nm, 1.76 mWcm^{-2}). Conditions: [B_{12}–TiO_2] = 10 mg ([B_{12}] = 1.60×10^{-5} M), [**1**] = 4.0×10^{-3} M, solvent 6 mL under N_2 at room temperature. Reaction time = 24 h. Conversion of the substrate and the product yield are based on the initial concentration of the substrate. [b]Each volume % of MeOH was added to MeCN.

α-Trifluoromethyl styrene (**1**) reduction by the B_{12}–TiO_2 was performed in MeOH at room temperature under UV light irradiation. In this reaction, MeOH was used as the solvent and a hole scavenger was used in the TiO_2 valence band. The hydrogenated product, *α*-trifluoromethyl ethylbenzene (**2**) and defluorinated product, *β*,*β*-difluoro-*α*-methylstyrene (**3**) were produced in 70% yield and in 29% yield, respectively, which indicated that **2** was main product in MeOH (entry 1 in Table 1). To improve the production of **3**, a mixture of MeCN and MeOH was used to control the protonic solvent ratio. With decreasing amount of MeOH (2.3 v%), the ratio of the **3** production was improved to be 3.8, while the substrate conversion decreased to be 72% (entry 2 in Table 1). A moderate yield of **3** was obtained in MeCN containing 17 vol% MeOH, because a sufficient amount of MeOH was required as an h_{VB}^+ scavenger.[58,59] Control experiments indicated that MeOH, light irradiation, and the B_{12} derivatives were essential for promoting this reaction. Other *p*-

substituted *α*-trifluoromethyl styrenes (**4**, **7**, **10**, **13**, and **16**) are tolerated under optimized condition as shown in Figure 5a, producing the corresponding *gem*-difluoroolefins (**5**, **8**, **11**, **14**, and **17**) in moderate yields. The reduction of *α*-difluoromethyl styrene (**19**) was also catalyzed by B_{12}–TiO_2 to yield *β*-fluoro-*α*-methylstyrenes with 45% of **20** and 24% of **21** (Figure 5b).

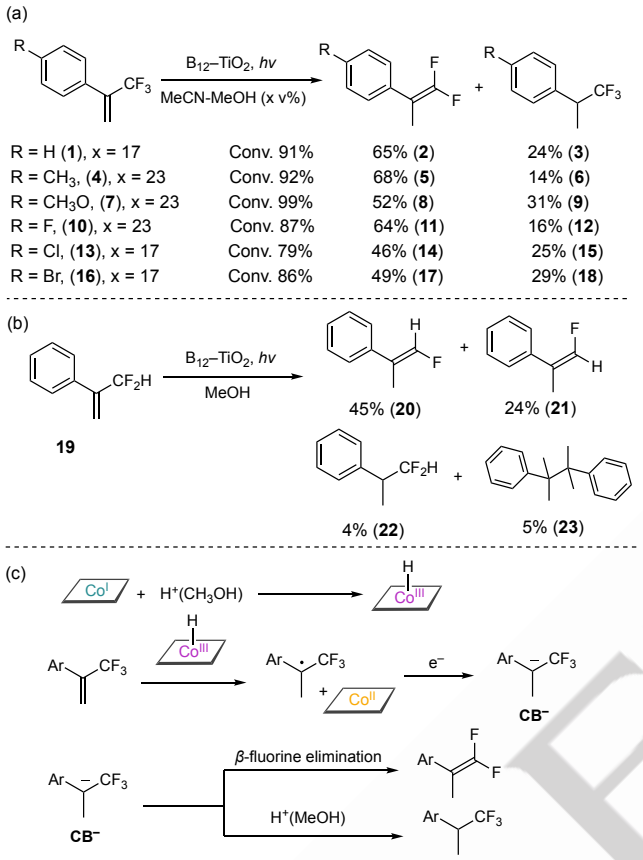


Figure 5. (a) Substrate scope for other trifluoromethyl styrene derivatives, (b) reduction of *α*-difluoromethyl styrene, (c) proposed mechanism of trifluoromethyl styrene reduction by B_{12}–TiO_2 under UV irradiation.

The proposed reaction mechanism using B_{12}–TiO_2 is illustrated in Figure 5c. Nucleophilic Co(I) species were generated by the two-electron reduction of Co(III) on TiO_2 during irradiation with UV light. The Co(I) species reacts with a proton from MeOH to produce the Co(III)–H. The Co(III)–H complex show the hydrogen radical character and hydrogen radical attacks at the *β*-position of the styrene derivatives to produce the *α*-radical intermediate and the Co(II) species. Then, the *α*-radical intermediate could be reduced by TiO_2 due to the electron withdrawing properties of the CF_3 group to produce a carbanion intermediate. The carbanion having a CF_3 group at the *α*-position is known to allow *β*-fluorine elimination to form the *gem*-difluoroolefin and fluoride ion. The following protonation of **CB**$^-$ lead to produce hydrogenated product.

Notably, this reaction proceeded under mild conditions without H_2 gas in a special reaction vessel. Thus, This B_{12} inspired reaction is a green and sustainable method for *gem*-difluoroolefin synthesis.

3-2. Visible Light Responsive TiO_2–B_{12} system

B_{12}–TiO_2 shows high catalytic activity for dehalogenation and organic synthesis under UV light irradiation. On the other hand, B_{12}–TiO_2 cannot utilize visible light because of its wide band gap of the TiO_2 (E_g = 3.2 eV). To overcome this issue, Song *et al.*, reported a novel visible light responsive B_{12}- based hybrid catalyst, B_{12}–TiO_2–Ru(II) (Figure 6), and its catalytic activity for visible light-driven DDT dichlorination.[60]

The B_{12}–TiO_2–Ru(II) was prepared by immobilizing a B_{12} derivative and trisbipyridine ruthenium, $Ru(dcb)(bpy)_2(PF_6)_2$ on the surface of mesoporous anatase TiO_2 microspheres. To investigate the visible light-driven Co(I) formation of the B_{12}–TiO_2–Ru(II), the UV-vis spectral change was measured in methanol containing a sacrificial reductant triethanolamine (TEOA) under visible light (λ ≥ 420 nm). After visible light irradiation for 25 min, a characteristic peak at 392 nm was clearly observed, indicating that Co(I) species were effectively produced on the surface of TiO_2 under visible light irradiation. In contrast, slow Co(I) formation was observed without TiO_2. Based on this comparison, TiO_2 effectively accelerates the formation of Co(I) species, which is attributed to the semiconductor property of TiO_2 as an electron mediator, which not only promotes electron transfer from Ru(II) to the cobalt center, but also effectively suppresses the back electron transfer process between the Co(I) and Ru(II) complexes.

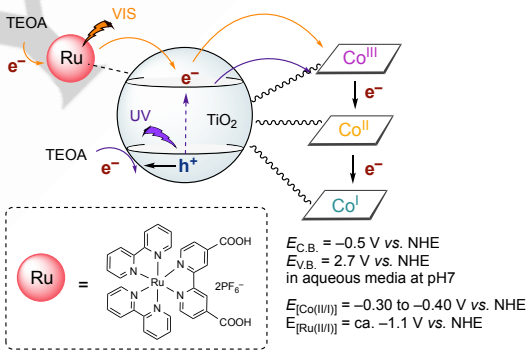


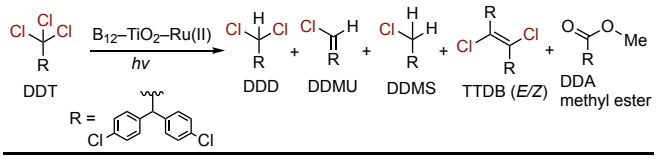
Figure 6. Electron transfer mechanism of B_{12}–TiO_2–Ru(II) under sunlight.

The visible-light photocatalytic activity of the hybrid B_{12}–TiO_2–Ru(II) for DDT dechlorination was investigated using TEOA as a hole scavenger in the valence band in methanol. By using the hybrid B_{12}–TiO_2–Ru(II) as catalyst, DDT conversion was 65% only after 10 min of visible light irradiation, and four kinds of dechlorinated products were obtained: DDD, DDMU, TTDB (*E*/*Z*), and DDA methyl ester in 35%, 4%, 9%, and 3% yields, respectively (entry 1 in Table 2). When the irradiation time was extended to 30 min, DDT was fully converted to di-dechlorinated products with high efficiency (entry 2 in Table 2). Control experiments showed that visible light irradiation, B_{12} derivatives, Ru(II) complexes, and TiO_2 were necessary for the desired reactivity. Furthermore, DDT dechlorination was performed using a sunlight simulator to evaluate the co-photosensitizing effect of TiO_2 and the Ru(II) complex on B_{12} catalysis. After 10 minutes irradiation, the DDT conversion reached 100% in the B_{12}–TiO_2–Ru(II), which was still 1.4 times higher than that of the B_{12}–TiO_2 and 1.5 times higher than that of the B_{12}–TiO_2–Ru(II) under visible

light irradiation (entry 3 in Table 2). Thus, the hybrid B_{12}–TiO_2–Ru(II) realized the utilization of both UV and visible light with high efficiency.

B_{12}–TiO_2-Ru(II) is efficient for the full utilization of solar energy and can be easily applied to the design of green catalysts.

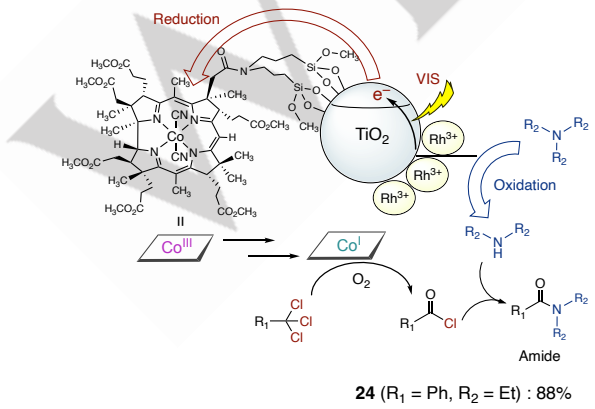
Table 2. Photocatalytic dechlorination of DDT catalyzed by B_{12}–TiO_2–Ru(II).[a]



entry	catalyst	time/ min	conv./ % [b]	Product yield /% [b] DDD	DDMU	DDMS	TTDB (E/Z)	DDAester
1	B_{12}–TiO_2–Ru(II)	10	65	35	4	Trace	9	3
2	B_{12}–TiO_2–Ru(II)	30	100	0	40	13	20	6
3[c]	B_{12}–TiO_2–Ru(II)	10	100	29	15	5	19	5
4[c]	B_{12}–TiO_2	10	74	25	2	Trace	20	4

[a]B_{12}–TiO_2–Ru(II) = 3 mg, [DDT] = 2.4 × 10^{-3} M, [TEOA] = 0.2 M, MeOH: 5 mL, irradiation: λ ≥ 420 nm, 50 mW cm^{-2}, distance: 10 cm. [b]DDT conversion and the product yields were determined by ^{1}H HMR. [c]Irradiation of simulated sunlight.

The surface modification of TiO_2 with inorganic compounds, such as rhodium(III) ions[61–63] and platinum ions[64], is a useful and convenient strategy for preparing the visible light-responsive TiO_2 as well as the modification of TiO_2 with organic compounds.[65] The visible light absorption band is ascribed to the surface charge transfer band of the modified TiO_2. Among the surface modified TiO_2, metal ion modification is a promising method for the development of a good catalyst due to its high stability and excellent charge separations. In 2020, Shichijo *et al.,* synthesized a visible-light-responsive B_{12} hybrid catalyst, B_{12}–Rh^{3+}/TiO_2, utilizing rhodium-modified TiO_2 (Rh^{3+}/TiO_2), as shown in Figure 7. Additionally, they developed a unique visible light-driven photoduet reaction for amide synthesis catalyzed by B_{12}–Rh^{3+}/TiO_2 under visible light irradiation under mild conditions (Figure 7).[66]



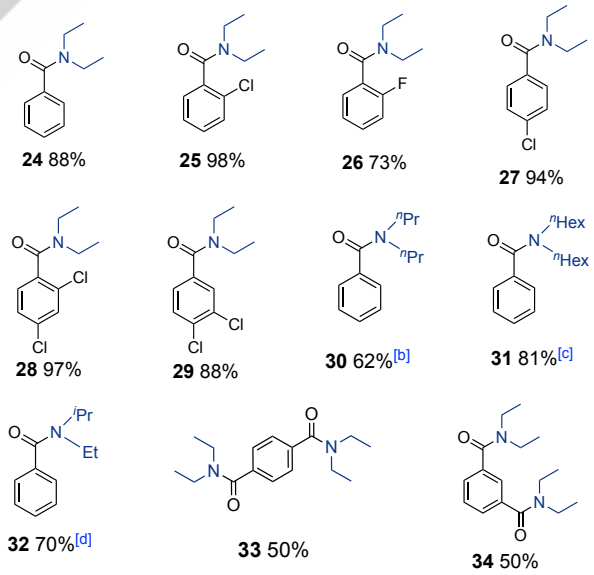
24 (R_1 = Ph, R_2 = Et) : 88%

Figure 7. Visible light-driven photo-duet reaction for amide formation catalyzed by B_{12}–Rh^{3+}/TiO_2 under air.

B_{12}–Rh^{3+}/TiO_2 was prepared by covalent immobilization of a B_{12} derivative with two trimethylsilyl groups on Rh^{3+}/TiO_2. The formation of Co(I) species of the B_{12} derivatives on the surface of Rh^{3+}/TiO_2 was examined by diffuse reflectance (DR) UV-vis spectroscopy under visible-light irradiation. The B_{12}–Rh^{3+}/TiO_2 suspended in MeCN containing 0.1 M triethylamine (Et_3N) exhibited the characteristic absorption of the Co(I) state of the B_{12} derivative at 390 nm after visible light irradiation (λ ≥ 420 nm).

The visible-light-driven photoduet reaction for amide synthesis was performed using B_{12}–Rh^{3+}/TiO_2, benzotrichloride ($PhCCl_3$), and Et_3N as the catalyst, substrate, and nucleophile, respectively. The *N,N*-diethylbenzamide (**24**) was produced in 88% yield after 3 h visible light irradiation (λ ≥ 420 nm). Control experiments indicated the need for Rh^{3+} ions, B_{12} derivatives, and visible light irradiation. The scope of the visible-light-duet reaction for amide synthesis is summarized in Table 3. Benzotrichloride derivatives with various substituents on the phenyl ring were tolerated under the optimized conditions, and the corresponding amides (**25**–**29**) were produced in good yields. Other tertiary amines were also used in this reaction, producing the corresponding amides (**30** and **32**) in moderate to good yields. In this photoduet reaction, the tertiary amines acted as an electron source for the hole scavenger B_{12}–Rh^{3+}/TiO_2 and were effectively converted to dialkyl amines. The resulting Co(I) species can react with benzotrichloride derivatives to form benzoyl chlorides in the presence of oxygen. The reaction between benzoyl chlorides and dialkyl amines produces the corresponding amides.

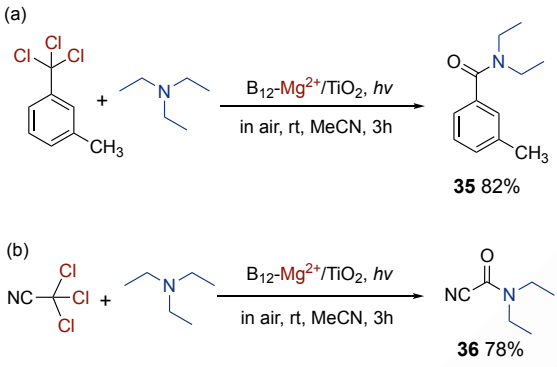
Table 3. Scope of reaction for amidation of benzotrichlorides in air under visible light irradiation.[a]



[a]Conditions: B_{12}–Rh^{3+}/TiO_2 = 20 mg ([B_{12}] = 1.97×10^{-5} M); [substrate] = 3.0×10^{-3} M; [Et_3N] = 1.0×10^{-1} M, solvent: 5.0 mL of CH_3CN at room temperature in air. The yield of the products was based on the initial concentration of the substrate. [b][tripropylamine] = 1.0 × 10^{-1} M. [c][trihexylamine] = 1.0 × 10^{-1} M. [d][diisopropylethylamine] = 1.0 × 10^{-1} M.

The same authors reported the development of visible light-driven hybrid catalysts composed of earth-abundant metal ion-modified TiO_2 and B_{12} derivatives (B_{12}–M^{n+}/TiO_2).[67] Metal ions, such as Cu^{2+}, Ni^{2+}, Fe^{2+}, Zn^{2+}, Mn^{2+}, Al^{3+}, and Mg^{2+}, were used to synthesize B_{12}–M^{n+}/TiO_2s. Both B_{12}–M^{n+}/TiO_2s effectively produced Co(I) species under visible-light irradiation as well as the B_{12}–Rh^{3+}/TiO_2. Thus, the use of abundant and inexpensive metal ions such as Mg^{2+} has enabled the development of visible-light-responsive hybrid catalysts. B_{12}–Mg^{2+}/TiO_2, which showed the highest catalytic activity of all the prepared B_{12}–M^{n+}/TiO_2, promoted DEET (**35**) or *N,N*-diethylcyanoformamide (**36**) formation in high yields under visible light irradiation (Scheme 5).

B_{12}–M^{n+}/TiO_2s is useful for green and sustainable organic synthesis using renewable solar energy.



Scheme 5. Photo-duet reaction for amide formation catalyzed by B_{12}–Mg_{2+}/TiO_2; (a) DEET formation, (b) *N,N*-diethylcyanoformamide.

3-3. MOF–B_{12} system (B_{12}–MOF)

MOFs are potent photosensitizers for heterogeneous dual-catalyst systems and TiO_2 photocatalysts. Xu *et al.,* developed a MOF-B_{12} system as a new bio-inspired heterogeneous catalyst (Figure 8a).[68] The porous MOF absorbed B_{12} derivatives, and the Ru(II) photosensitizer and B_{12}–Ru@MOF promoted the dichlorination of DDT and 1,2-migration reactions. Recently, photoredox-active MOFs such as MIL-125-NH2(Ti) have emerged as versatile photocatalysts because of their ultrahigh porosity, good e^-–h^+ separation, and visible-light absorption capacity.[69] In 2023, Gryko *et al.,* developed a heterogeneous dual-catalyst system composed of vitamin B_{12} and MIL-125-NH_2(Ti) following a previous method (Figure 8b).[70]

To investigate the visible-light-driven Co(I) formation, a mixture of vitamin B_{12} and a large excess of MIL-125-NH_2(Ti) in EtOH was irradiated with blue light (450 nm) for 15 min. MIL-125-NH_2(Ti) effectively reduced the central Co ion to produce Co(I) species under blue light irradiation in the presence of *N,N*-diisopropylethylamine (DIPEA). The newly developed system was used for the dehalogenation of DDT under blue light irradiation. In the presence of the newly developed catalytic system, the dehalogenation of DDT yields three main products, DDMS and TTDB, with full substrate conversion, indicating the utility of this newly developed system.

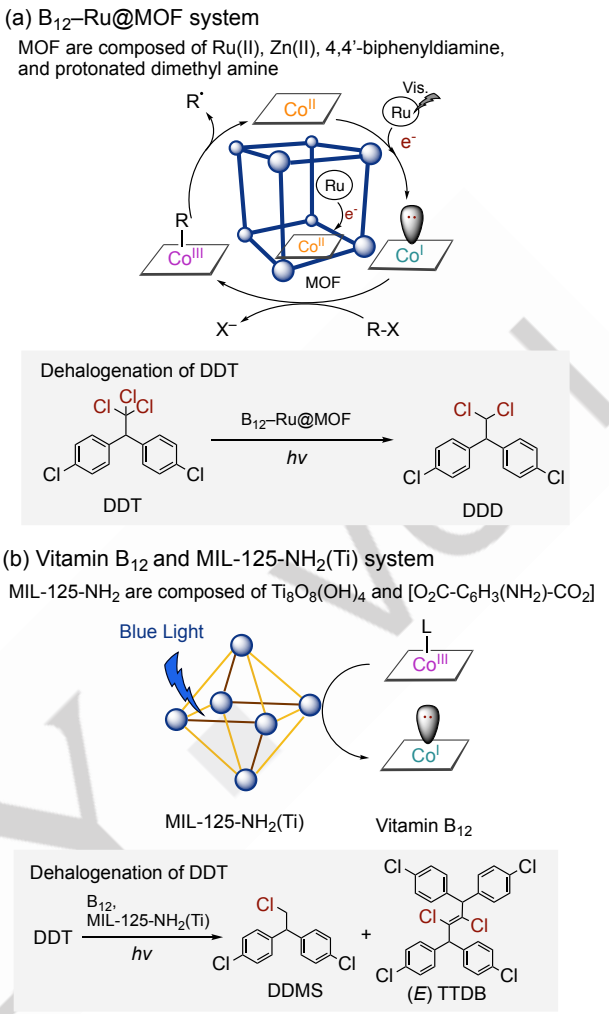


Figure 8. MOF-B_{12} system; (a) B_{12}–Ru@MOF, (b) vitamin B_{12} and MIL-125-NH_2(Ti).

In summary, a dual-catalyst system that combines heterogeneous photocatalysts, such as TiO_2s and MOFs, with a B_{12} derivative is presented. The synergistic effect of dual-catalysis involves the efficient formation of Co(I) species via electron transfer from the photoexcited photocatalyst to the B_{12} derivative. This enables green molecular transformations by minimizing the use of chemical reagents and utilizing alternative energy sources. Thus, a dual-catalyst system consisting of photocatalysts and B_{12} derivatives is expected to be an excellent catalytic system that contributes to the development of green and sustainable chemistry.

4. Summary and Outlook

In this concept, we summarize the interesting synergistic effects of dual-catalysis of metal complexes and semiconductor photocatalysts on photocatalytic reactions. The dual-catalyst system comprising vitamin B_{12} and semiconductor photocatalysts

effectively promotes light-driven organic molecular transformations, such as dehalogenation reactions and radical organic syntheses. The B_{12}–TiO_2 produces catalytically active Co(I) species under UV irradiation, which promotes the reduction of *α*-difluoromethylstyrene to form *gem*-difluoroolefin. While B_{12}–TiO_2 is not compatible with visible-light irradiation, B_{12}–TiO_2–Ru(II) and B_{12}–M^{n+}/TiO_2 are operable over a wide wavelength range from UV to visible light. Moreover, B_{12}–MOF is an attractive dual-catalyst system that can respond to visible light. These visible-light-driven dual-catalyst systems have enabled the development of visible-light-driven organic molecular transformations such as the dehalogenation of DDT and amidation from $RCCl_3$s. Thus, the dual-catalysis of vitamin B_{12} and semiconductor photocatalysts can achieve a more environment-friendly and sustainable organic synthesis by minimizing the use of chemical reagents and utilizing alternative energy sources.

Dual-catalyst systems for photochemical CO_2 reduction have been developed, along with a B_{12}-based dual-catalyst system.

Therefore, the dual-catalysis of metal complexes and heterogeneous photocatalysts will significantly contribute to the development of green and sustainable chemistry.

5. Acknowledgements

This study was partially supported by a Grant from the Sumitomo Foundation (No. 2330075). This study was supported by a Grant-in-Aid for JSPS Fellows (No. 22KJ2382). Part of the study was performed under the Cooperative Research Program of “Network Joint Research Center for Materials and Devices: Dynamic Alliance for Open Innovation Bridging Human, Environment and Materials” (Nos. 20234028 and 20235025) and a Grant from the Yashima Environment Technology Foundation.

Keywords: Amide Synthesis • Dual-Catalysis • Heterogeneous Photocatalyst • Vitamin B_{12}

[1] T. P. Anastas, B. J. Zimmerman, *Environ. Sci. Technol.* **2003**, *37*, 94A-101A.

[2] P. Anastas, N. Eghbali, *Chem. Soc. Rev.* **2010**, *39*, 301–312.

[3] M. Saraf, M. A. Roy, F. Yarur Villanueva, A. Kundu, H.-V. Tran, M. Ghosh, S. Ezenwa, G. Gastelu, E. A. Prebihalo, L. J. Cala, S. R. Cleary, G. Devineni, G. A. Lee, G. C. Umenweke, R. F. Koby, R. Nixon, A. Voutchkova, A. Moores, *ACS Sustain. Chem. Eng.* **2023**, *11*, 13822–13835.

[4] A. Paul, John. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, **1998**.

[5] M. H. Shaw, J. Twilton, D. W. C. MacMillan, *J. Org. Chem.* **2016**, *81*, 6898–6926.

[6] C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.* **2013**, *113*, 5322–5363.

[7] D. Friedmann, A. Hakki, H. Kim, W. Choi, D. Bahnemann, *Green Chem.* **2016**, *18*, 5391–5411.

[8] H. Cheng, W. Xu, *Org. Biomol. Chem.* **2019**, *17*, 9977–9989.

[9] V. Pascanu, G. González Miera, A. K. Inge, B. Martín-Matute, *J. Am. Chem. Soc.* **2019**, *141*, 7223–7234.

[10] D. Franchi, Z. Amara, *ACS Sustain. Chem. Eng.* **2020**, *8*, 15405–15429.

[11] S. Gisbertz, B. Pieber, *ChemPhotoChem* **2020**, *4*, 454–475.

[12] Y. Okada, *Chem. Rec.* **2021**, *21*, 2223–2238.

[13] K. L. Skubi, T. R. Blum, T. P. Yoon, *Chem. Rev.* **2016**, *116*, 10035–10074.

[14] A. Y. Chan, I. B. Perry, N. B. Bissonnette, B. F. Buksh, G. A. Edwards, L. I. Frye, O. L. Garry, M. N. Lavagnino, B. X. Li, Y. Liang, E. Mao, A. Millet, J. V. Oakley, N. L. Reed, H. A. Sakai, C. P. Seath, D. W. C. MacMillan, *Chem. Rev.* **2022**, *122*, 1485–1542.

[15] M. Giedyk, K. Goliszewska, D. Gryko, *Chem. Soc. Rev.* **2015**, *44*, 3391–3404.

[16] H. Shimakoshi, Y. Hisaeda, *Chem. Rec.* **2021**, *21*, 2080–2094.

[17] T. Wdowik, D. Gryko, *ACS Catal.* **2022**, *12*, 6517–6531.

[18] H. Shimakoshi, M. Tokunaga, T. Baba, Y. Hisaeda, *Chem. Commun.* **2004**, 2242.

[19] H. Shimakoshi, M. Nishi, A. Tanaka, K. Chikama, Y. Hisaeda, *Chem. Commun.* **2011**, *47*, 6548–6550.

[20] H. Tian, H. Shimakoshi, G. Park, S. Kim, Y. You, Y. Hisaeda, *Dalton Trans.* **2018**, *47*, 675–683.

[21] L. Chen, Y. Kametani, K. Imamura, T. Abe, Y. Shiota, K. Yoshizawa, Y. Hisaeda, H. Shimakoshi, *Chem. Commun.* **2019**, *55*, 13070–13073.

[22] H. Tian, H. Shimakoshi, T. Ono, Y. Hisaeda, *ChemPlusChem* **2019**, *84*, 237–240.

[23] L. Chen, Y. Hisaeda, H. Shimakoshi, *Adv. Synth. Catal.* **2019**, *361*, 2877–2884.

[24] D. E. Yerien, A. Postigo, M. Baroncini, S. Barata-Vallejo, *Green Chem.* **2021**, *23*, 8147–8153.

[25] Y. Anai, K. Shichijo, M. Fujitsuka, Y. Hisaeda, H. Shimakoshi, *Chem. Commun.* **2020**, *56*, 11945–11948.

[26] H. Shimakoshi, Y. Hisaeda, *ChemPlusChem* **2017**, *82*, 18–29.

[27] H. Shimakoshi, E. Sakumori, K. Kaneko, Y. Hisaeda, *Chem. Lett.* **2009**, *38*, 468–469.

[28] H. Shimakoshi, M. Abiru, S. I. Izumi, Y. Hisaeda, *Chem. Commun.* **2009**, *2*, 6427–6429.

[29] H. Shimakoshi, M. Abiru, K. Kuroiwa, N. Kimizuka, M. Watanabe, Y. Hisaeda, *Bull. Chem. Soc. Jpn.* **2010**, *83*, 170–172.

[30] H. Shimakoshi, Y. Hisaeda, *ChemPlusChem* **2014**, *79*, 1250–1253.

[31] H. Shimakoshi, Y. Hisaeda, *Angew. Chem. Int. Ed.* **2015**, *54*, 15439–15443.

[32] B. Kräutler, D. Arigoni, T. G. Bernard, *Vitamin B12 and B12-Proteins*, Wiley Verlag GmbH, Weinheim, **1998**.

[33] C. L. Drennan, S. Huang, J. T. Drummond, R. G. Matthews, M. L. Ludwig, *Science* **1994**, *266*, 1669–1674.

[34] R. G. Matthews, *Acc. Chem. Res. 2001,* **2001**, *34*, 681–689.

[35] R. Banerjee, S. W. Ragsdale, *Annu. Rev. Biochem.* **2003**, *72*, 209–247.

[36] T. Toraya, *Chem. Rev.* **2003**, *103*, 2095–2127.

[37] K. L. Brown, *Chem. Rev.* **2005**, *105*, 2075–2149.

[38] K. L. Brown, *Dalton Trans.* **2006**, *6*, 1123–1133.

[39] K. Gruber, B. Puffer, B. Kräutler, *Chem. Soc. Rev.* **2011**, *40*, 4346–4363.

[40] K. Proinsias, M. Giedyk, D. Gryko, *Chem. Soc. Rev.* **2013**, *42*, 6605–6619.

[41] M. Ociepa, O. Baka, J. Narodowiec, D. Gryko, *Adv. Synth. Catal.* **2017**, *359*, 3560–3565.

[42] M. Ociepa, A. J. Wierzba, J. Turkowska, D. Gryko, *J. Am. Chem. Soc.*

2020, *142*, 5355−5361.

[43] Z. Luo, K. Imamura, Y. Shiota, K. Yoshizawa, Y. Hisaeda, H. Shimakoshi, *J. Org. Chem.* **2021**, *86*, 5983–5990.

[44] K. Komeyama, T. Michiyuki, Y. Teshima, I. Osaka, *RSC Adv.* **2021**, *11*, 3539–3546.

[45] A. Potrząsaj, M. Musiejuk, W. Chaładaj, M. Giedyk, D. Gryko, *J. Am. Chem. Soc.* **2021**, *143*, 9368–9376.

[46] M. Moniruzzaman, Y. Yano, T. Ono, H. Shimakoshi, Y. Shiota, K. Yoshizawa, Y. Hisaeda, *J. Org. Chem.* **2021**, *86*, 16134–16143.

[47] S. Dadashi-Silab, C. Preston-Herrera, E. E. Stache, *J. Am. Chem. Soc.* **2023**, *145*, 19387–19395.

[48] A. Fujishima, K. Honda, *Nature* **1972**, *238*, 37–38.

[49] M. G. B. O'Regan, *Nature* **1991**, *353*, 737–740.

[50] R. Wang, K. Hashimoto, A. Fujishima, M. Chikuni, E. Kojima, A. Kitamura, M. Shimohigoshi, T. Watanabe, *Nature* **1997**, *338*, 431–432.

[51] A. Fujishima, T. N. Rao, D. A. Tryk, *J. Photochem. Photobiol. C Photochem. Rev.* **2000**, *1*, 1–21.

[52] T. Hirakawa, Y. Nosaka, *Langmuir* **2002**, *18*, 3247–3254.

[53] K. Hashimoto, H. Irie, A. Fujishima, *Jpn. J. Appl. Phys.* **2006**, *44*, 8269–8285.

[54] M. Ni, M. K. H. Leung, D. Y. C. Leung, K. Sumathy, *Renew. Sust. Energ. Rev.* **2007**, *11*, 401–425.

[55] A. Fujishima, X. Zhang, D. A. Tryk, *Surf. Sci. Rep.* **2008**, *63*, 515–582.

[56] J. Schneider, M. Matsuoka, M. Takeuchi, J. Zhang, Y. Horiuchi, M. Anpo, D. W. Bahnemann, *Chem. Rev.* **2014**, *114*, 9919–9986.

[57] H. Tian, H. Shimakoshi, K. Imamura, Y. Shiota, K. Yoshizawa, Y. Hisaeda, *Chem. Commun.* **2017**, *53*, 9478–9481.

[58] Y. Tamaki, K. Hara, R. Katoh, M. Tachiya, A. Furube, *J. Phys. Chem. C* **2009**, *113*, 11741–11746.

[59] O. I. Mide, Y. Zhang, K. R. Cromack, A. D. Trifunac, M. C. Thurnauer, *J. Phys. Chem.* **1993**, *97*, 13284–13288.

[60] Y. Sun, W. Zhang, T. Y. Ma, Y. Zhang, H. Shimakoshi, Y. Hisaeda, X. M. Song, *RSC Adv.* **2018**, *8*, 662–670.

[61] K. Hashimoto, K. Sumida, S. Kitano, K. Yamamoto, N. Kondo, Y. Kera, H. Kominami, *Catal. Today* **2009**, *144*, 37–41.

[62] S. Kitano, K. Hashimoto, H. Kominami, *Chem. Lett.* **2010**, *39*, 627–629.

[63] S. Kitano, N. Murakami, T. Ohno, Y. Mitani, Y. Nosaka, H. Asakura, K. Teramura, T. Tanaka, H. Tada, K. Hashimoto, H. Kominami, *J. Phys. Chem. C* **2013**, *117*, 11008–11016.

[64] H. Kisch, L. Zang, C. Lange, W. F. Maier, C. Antonius, D. Meissner, *Angew. Chem. Int. Ed.* **1998**, *37*, 3034–3036.

[65] A. Ajmal, I. Majeed, R. N. Malik, H. Idriss, M. A. Nadeem, *RSC Adv.* **2014**, *4*, 37003–37026.

[66] K. Shichijo, M. Fujitsuka, Y. Hisaeda, H. Shimakoshi, *J. Organomet. Chem.* **2020**, *907*, 121058.

[67] K. Shichijo, M. Watanabe, Y. Hisaeda, H. Shimakoshi, *Bull. Chem. Soc. Jpn.* **2022**, *95*, 1016–1024.

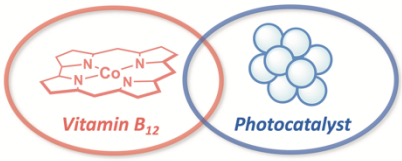
[68] J. Xu, H. Shimakoshi, Y. Hisaeda, *J. Organomet. Chem.* **2015**, *782*, 89–95.

[69] Q. Wang, Q. Gao, A. M. Al-Enizi, A. Nafady, S. Ma, *Inorg. Chem. Front.* **2020**, *7*, 300–339.

[70] K. R. Dworakowski, A. Chołuj, M. J. Chmielewski, D. Gryko, *Chem. Commun.* **2023**, *59*, 11236–11239.

Table of Contents

Dual Catalysis of Vitamin B_{12} and Heterogeneous Photocatalyst



Vitamin B_{12}-based Dual Catalyst for Green and Sustainable Molecular Transformation

This concept focuses on the synergies between metal complexes and heterogeneous photocatalysts in dual-catalyst systems. The B_{12}-based dual-catalyst enables green and sustainable molecular transformations, including the light-driven dehalogenation of toxic alkyl halides (DDT), *gem*-difluoroolefin synthesis, and amide synthesis from $RCCl_3$.