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A Literature Review on the advancement of Photocatalysis

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Abstract

Photocatalysis has been considered as one of the most favourable methodology for solving the energy crises and the environmental pollution. Henceforth, photocatalysis applications have a lot remarkable attention in various fields. The current review article employs a systematic review process based on the PRISMA mechanism to investigate several types of photocatalysts for varied applications. The research papers were taken during the years 2017 and 2021. The progress in the modification and development of photocatalysts is discussed in this article. In addition, possible methods for enhancing photocatalytic activity and separating photocatalysts from reaction medium are reviewed in order to offer a future direction in an effective photocatalyst design for a variety of applications.

Keywords – Systematic Literature Review, Photocatalyst, environmental pollution, energy crisis.

1. Introduction

The overuse of fossil fuel resources has arisen because of the fast evolution of several industries. This has intensified the global energy crisis and resulted in various environmental issues that causes a major threat to long-term growth of human society (Corti et al. 2021). Industrial residues are one of the most significant environmental hazards, as they can enclose extremely polluting chemicals such as solvents, pesticides, cyanide, and metals such as mercury, lead, cadmium, and drugs. All of which turn out in endangering natural cycles and, in many cases, it directly affects the human health. Furthermore, these substances have the potential to be exceedingly poisonous, carcinogenic, and refractory in nature. Because of the high solubility and stability of numerous compounds in water, treatment of industrial residual effluent into safer levels is a greater challenge (Lim et al. 2011). Hence, several procedures have been proposed over the years and are now being used to remove these dangerous chemicals. One such mechanism is photo catalysis, which is a viable method for addressing future environmental and energy issues. Therefore, several works had been gone into for developing photo catalysts.

The growth of stable, efficient, and low-cost photo catalysts is critical in practical case. Hence, effectivemechanisms should be handled such that the catalyst, the pollutant, and the illumination source must all be within close proximity or mutually related for the photocatalysts to work effectively. Photo catalysis has proven to be an intriguing approach for improving traditional wastewater treatment (Zuo et al. 2016). A photocatalyst isa well-defined method in which the activation of catalyst is accomplished by photon absorbtion and can speed up a reaction without any energy consumption. Because of this technique's ability to perfectly mineralize the target contaminants, it is considered to be the best procedure for wastewater treatment. Many semiconductors have been identified as possible photocatalysts under solar light, including TiO_2, ZnO, SnO_2, Fe_2O_3, $BiVO_4$, Cu_2O, and WO_3 (Yuan et al. 2021). They've been employed to catalyse a variety of reactions, like CO_2 reduction for hydrocarbon fuel production, water splitting for hydrogen production, hazardous gas decomposition, and organic pollutant degradation. Photocatalyst synthesis is a critical step in modifying the photocatalyst's structural and physical properties.

Furthermore, the capacity to comprehend and manage photo-absorption over the whole visible range with high photoactivity and stability can pave the way for further long-term applications (Kumar et al. 2018). However, current photocatalysts have a number of issues, including a wide energy bandgap, low visible light utilisation efficiency from solar energy, inadequate physicochemical stability of metallic semi-conductors, and a high recombination rate of photogenerated electron–hole pairs, all of which severely limit their practical application (Bresolin, Park, and Bahnemann 2020). Single-component photocatalysts struggle to meet all of these requirements at the same time. As a result, developing subsequent generation photocatalysts with low cost, good stability and high visible-light efficiency is critical. Photocatalytic systems based on the Z scheme increase the utility range of visible light, enhance the transport/separation of charge carrier, and increase the efficiency of photocatalytic activities significantly. The numerous types of photocatalysis used in various fields, as well as their synthesis processes, are fully reviewed in this article.

The residual of the article is divided into seven portions: section 2 discusses the methodology of research and steps for conducting a systematic review; section 3, 4 and 5 discusses the various types of photocatalysts, methods of photocatalytic activity and its applications; section 6 describes the review results; and finally, the section 7 provides the conclusion.

2. Research method

This section explores the methods for obtaining articles pertaining to a current research project via the online community. The investigation is based on a Systematic Review. The review focuses on a few of the specific research field, which aids in identifying and examining the study facts that are relevant to the research area. The analyses are divided into many steps, the first of which is the gathering of resources from standardised publications in order to conduct an ordered literature review. The source identification, eligibility, data screening, data inclusion and exclusion, data extraction and synthesis are all carried out. Fig.1 depicts the systematic review process.

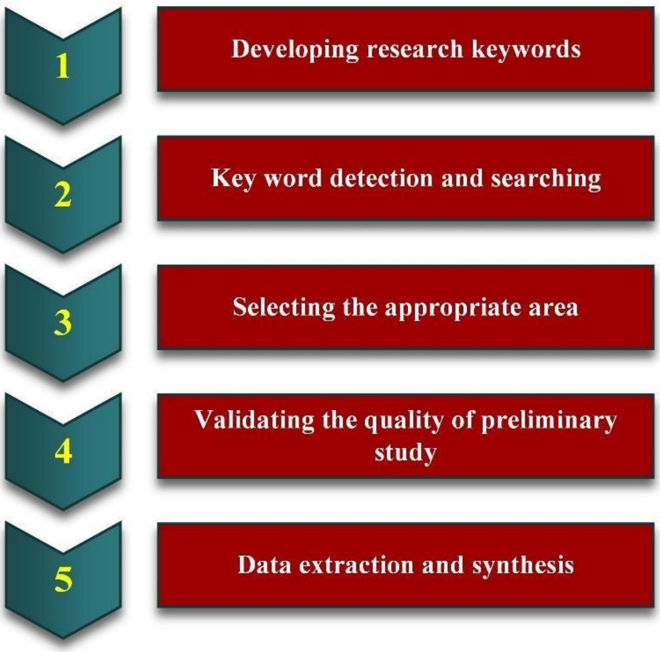

Fig.1 Major steps in the systematic review

2.1. Detecting keywords and searching procedure

The keyword detection and search technique is carried out by filtering the search items and determining the research time. Through the pilot search, the searching area is confined to electronic databases, with a limited search time commencing in 2017 and ending in 2021. Because each database has distinct search techniques, the search Boolean operators are more valuable to use. In most databases, an overarching search string is used, with small differences in the others. The search was conducted using an online electronic search that depend on journal databases such as Elsevier, Springer, Google Scholar, Scopus, Wiley online library, and others to search through the online systematic records. These online databases were chosen because they include a large number of records on the photocatalyst development process, as well as being the most appropriate databases for providing comprehensive information about the study subject.

2.2 Choosing and evaluating the quality of primary studies

Following the completion of the keyword and search operation, the inclusion and exclusion criteria are used to select and assess the quality of primary research. This criterion aids in the selection of papers related to the current research project. Only regular journal papers from some of the standard databases that focus on photocatalyst development were chosen for this kind, with review articles and book series being eliminated. Furthermore, publications from the years 2017 to 2021 were chosen because this would be an appropriate time frame for completing the investigation. Furthermore, studies that focus solely on design of photocatalysts and its applications is considered for examination; all others are discarded. Table 1 illustrates the inclusion and exclusion criteria of the present review procedure.

Table 1: Inclusion and exclusion criteria for current review procedure

Measures	**Inclusion criteria**	**Exclusion criteria**
Availability of Literature	full-text	Papers with no availability of full text is excluded
Language	English	Non-English papers are excluded
Timeline	Between 2017 and 2021	Gray papers (Papers without bibliographic data, such as date/type of publication, issue numbers, and volume numbers, were omitted, and papers published prior to 2017 were excluded)
Research question	Papers that responds to at least one research question	Identical papers (The most recent paper that contains the needed information is provided, while the others are not)

2.3. Data Abstraction and selection

The data extraction and synthesis stage must be completed first, followed by the research selection criteria. The resources and data obtained during the review are recorded on the data extraction form. It was performed by analysing the studies and extracting useful information from the collected papers. The keywords used in the study's search procedure are identified in the preliminary phase. For each online database, many keywords that are comparable and connected to study were selected from the thesaurus and prior studies.

Initially, 175 articles are taken for review, which includes the records obtained through database searching and additional records obtained from other sources. Then, systematic review process is undertaken to select the required articles for analysis. It includes 4 stages namely Identification, Screening, Eligibility and selection. In the initial phase, the keywords utilized in the searching procedure of the study are determined. In this stage, 55 duplicated articles were removed. Followed by this, the next stage is screening in which 70 articles were found to be suitable to be reviewed by removing the articles chosen in the year below 2017. The third phase is eligibility, in which the whole articles were examined. After an in-depth study, overall of 50 articles were neglected, as they didn't emphasis on the photocatalyst design. Finally, 20 articles were chosen for qualitative investigation. The complete review process is depicted in fig.2.

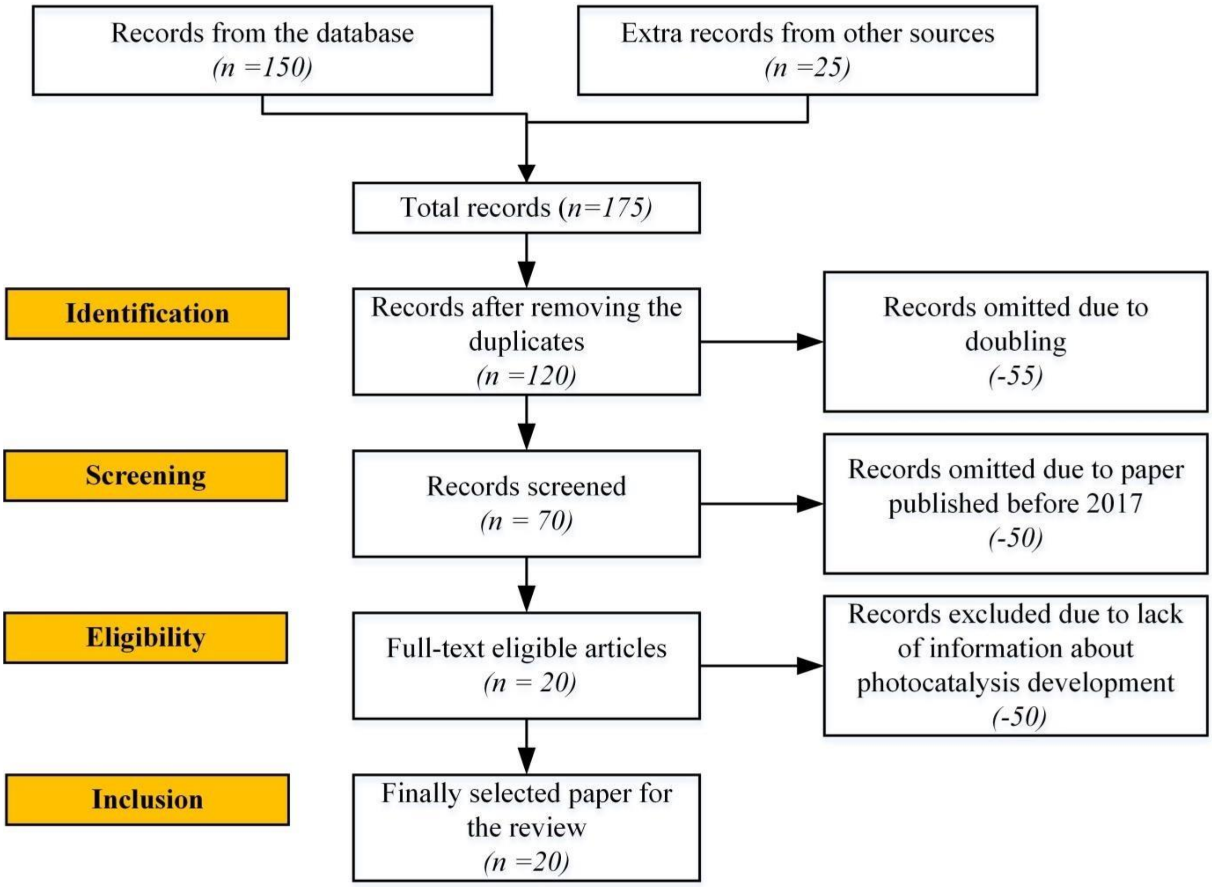

Fig.2 Complete review process

3. Various kinds of photocatalysts

3.1 Semiconductor based photocatalyst

Because of their high activity and stability, semiconductor photocatalysts have attracted increased attention (Opoku et al. 2017). Photocatalysis, which uses semiconductors to degrade poisonous and harmful organic molecules in industrial wastewater and drinking water, has been reported as a potential strategy. The semiconductor photocatalyst must meet several requirements, including non-toxicity, a narrower band gap to grip a big fraction of solar energy, long-term stability, cheap cost, chemical as well as biological inertness, and effective mobility of photogenerated charge carriers. When a semiconductor material building block is exposed to light with higher than same as that of its bandgap, an e^- from the VB is excited to the CB, making a hole to form in the valence band and e^- to form in the conduction band. The water splitting thermodynamic criteria would be met if the conduction and valence bands were aligned appropriately with respect to the reduction and oxidation potentials, respectively.

3.1.1 TiO_2

Because of its excellent photoactivity, lower cost, chemical and biological stability, and lower toxicity, TiO_2 has emerged as the most popular photocatalyst for water usage. The 3.2 eV and 3.0 eV bandgap energies for the anatase and rutile phases of TiO_2 allow for significant redox power under Ultraviolet irradiation. Except for specific categories of fluorinated compounds, heterogeneous photocatalysis with Ultraviolet radiation has been shown to be capable of degrading nearly all organics. From a photocatalytic, chemical, morphological, and optical standpoint, clean TiO_2 and TiO_2-based materials have both been extensively researched.

3.2 Residue based photocatalysts

A sample of activated carbon is used to assess the latent of heterogeneous photocatalysts derived from petrochemical industrial waste and agro-industrial wastes. In (da Silva et al. 2021), the activated carbon was made through carbonising black acacia and treating it with phosphoric acid before using it to make catalysts with different surface areas and complexity. Under UV–vis irradiation, these photocatalysts were then used to degrade phenol in water.

3.3 Heteroatom-doped photocatalysts

Heteroatom doping, which includes cation and anion doping has extensively been studied in order to alter the energy structure of semiconductors in order to achieve higher efficiency and highly stable photocatalysts. In general, doping foreign elements into semiconductors can regulate the band gap through the introduction of impurity levels in the forbidden energy band, which can then increase absorption of light and enhance the efficiency of separation of photogenerated carriers, thereby enhancing the stability and photocatalytic activity of the semiconductor.

4. Various methods for enhancing the photocatalytic activity

4.1 Photosensitization

TiO_2 has been employed for photodegradation of numerous pollutants and for energy conversion and it is one of the mostly used semiconductor photocatalysts. However, the existing solar energy for excitation of TiO_2 and the solar energy accomplishing the earth's surface are both relatively tiny, accounting for less than 5% of total sunshine. Lower efficiency in solar energy conversion and higher charge recombination rate of photogenerated holes and electrons are frequently two primary preventive issues for its widespread use. Several efforts have been taken to explore innovative techniques to adapt TiO_2. One of the methods is the photosensitization, which is an significant approach to stimulate the TiO_2 towards the visible light wavelength, to utilise the inexpensive visible light from solar energy and improve the efficiency of energy conversion in course of photocatalyst reactions. A photosensitizer collects light energy, converts it to chemical energy and transmits it to other photochemically non-reactive substrates under favourable conditions. An electrostatic, hydrophobic, or chemical contact can adsorb photosensitizer onto the semiconductor surface, which, upon activation, injects an electron into its conduction band.

4.2 Photocorrosion

Photocorrosion of semiconductors may occur when they are exposed to light. Photogenerated holes and electrons, both can contribute for decomposing the semiconductors, resulting in a variety of photocorrosion mechanisms in semiconductor-based photocatalysts. Furthermore, based upon whether the molecular oxygen is present in the reaction systems or not, photocorrosion mechanisms would be altered for semiconductor-based photocatalysts, such as metal sulphides, (Weng et al. 2019). Both photogenerated electrons and holes can cause semiconductors to corrode, resulting in a loss of photoactivity. In these situations, efficient exportation of photogenerated charge carriers from semiconductor surfaces appears to be a critical strategy for increasing their stability and preventing photocorrosion.

4.3 Hybridization

Cocatalysts are well known for their ability to serve as reaction sites for a variety of processes, Photocorrosion suppression in semiconductor-based photocatalysts, boosting charge separation, resulting in good performance in photocatalytic activity. Adding proper cocatalysts to semiconductors can often improve the photostability of compound photocatalysts by consuming or transferring photogenerated charge carriers in a timely manner.

5. Various applications of photocatalysts

Mercury, Zinc, Chromium, Selenium, Lead, and other heavy metals have all been removed from wastewater using heterogeneous photocatalysis. Photocatalysis' photoreducing capacity has been exploited to extract valuable metals from the industrial pollutants. It's also utilised in water decontamination, the removal of organic and inorganic impurities that might pollute water, as well as air and water purification.

Table 2: Photocatalysts and their synthesis methods

No	Reference	Photocatalytic activity	Light source	Photocatalyst	Method
1.	(Li et al. 2019)	Heteroatom Doping	Solar energy	Ammonia	Ammonia production by Haber–Bosch process
2.	(Tahir et al. 2017)	Metal doping	Visible light source	Tungsten trioxide (WO_3)	Hydrothermal method
3.	(Pascariu et al. 2020)	Cellulose acetate butyrate nanofibers with ammonium zincate	Visible light source	Carbon / ZnO nanostructures	Electrospinning method, Hydrothermal method
4.	(de O. Pereira et al. 2019)	Tar + Red mud (Fe_2O_3)	Germicidal lamp	TiO2/C/RM,	-
5.	(Bresolin, Park, and Bahnemann 2020)	-	Solar light	Metal Halide Perovskite	-
6.	(da Silva et al. 2021)	Ziegler-Natta catalyst slurry + Acacia bark	-	P25-TiO_2	Impregnation method
7.	(Rodríguez-González, Terashima, and Fujishima 2019)	TiO_2	LED light source	TiO_2 - PN	non-thermal plasma technologies
8.	(Ribeiro et al. 2020)	Rutile + Evonik	Solar energy	TiO_2/PET	-
9.	(Dong et al. 2018)	-	Visible light	$LiCuTa_3O_9$	-
10.	(Santos et al. 2019)	Polystyrene	Mercury vapour lamp	TiO_2	Impregnation method
11.	(Ani et al. 2018)	-	Solar light	TiO_2- and ZnO	
12.	(Rodríguez-Padrón, Luque, and Muñoz-Batista 2020)	-	Visible light	TiO_2, ZnO, and metal sulfides	Impregnation method

13.	(Abu-Dief and Mohamed 2021)	-	Visible light	Nanomaterials	-
14.	(Matos et al. 2017)	Dissolved Organic Carbon	Solar light	TiO_2-C	-
15.	Hisatomi and Domen 2019)	Conducting materials	Sunlight	NiO-loaded La-doped $NaTaO_3$ photocatalysts	Metal doping
16.	(Huang et al. 2020)	Ag/AgBr-δ-Bi2O3	Solar light	Bismuth based photocatalysts	Haber–Bosch process
17.	(Kumaresan et al. 2019)	Co(NO3)2·6H2O, Al(NO3)3·9H2O and urea	Visible-light	CoAl-LDHs/RGO nanocomposites	Solvothermal method
18.	(Zhang, Ke, and Yao 2018)	Pt, Pd, Al and alloys + Au, Ag or Cu	Visible light	Plasmonic photocatalysts	Atomic layer deposition
19.	(Hisatomi and Domen 2019)		Sunlight	Oxide photocatalysts	Doping
20.	(Pal et al. 2020)	$AgNO_3$ + NaOH	Visible light	Fe_3O_4/Ag/Ag_2O	Ultrasonication

Table 3: Photocatalysts and their energy value, stability and applications

No	**Reference**	**Bandgap energy**	**Stability**	**Application**	**Efficiency**
1.	(Li et al. 2019)	-	Stable	Environmental application-nitrogen fixation	-
2.	(Tahir et al. 2017)	2.4 to 2.8 eV	Stable	Waste water treatment	-
3.	(Pascariu et al. 2020)	2.51 eV	Stable	Degradation of dyes	97.97 %
4.	(de O. Pereira et al. 2019)	-	-	Removal of dyes	80 %
5.	(Bresolin, Park, and Bahnemann 2020)	-	-	Hydrogen evolution, carbon dioxide reduction, organic contaminant degradation	-
6.	(da Silva et al. 2021)	2.55–3.65 eV	Stable	Phenol degradation, waste water treatment	-
7.	(Rodríguez-González, Terashima, and Fujishima 2019)	-	Stable	Agricultural application	-

8.	(Ribeiro et al. 2020)	-	Stable	Degradation of textile dyes	-
9.	(Dong et al. 2018)	2.48 eV	Stable	Solar water splitting	-
10.	(Santos et al. 2019)	-	-	Removal of food dyes	-
11.	(Ani et al. 2018)	3.02 eV	Stable	Pollutant degradation	-
12.	(Rodríguez-Padrón, Luque, and Muñoz-Batista 2020)	3.08 eV	Stable	Environmental application	-
13.	(Abu-Dief and Mohamed 2021)	-	-	Waste water treatment	-
14.	(Matos et al. 2017)	-	Stable	Water purification	-
15.	(Hisatomi and Domen 2019)	2.36 eV	Stable	Solar hydrogen production	-
16.	(Huang et al. 2020)	2.25 eV	Stable	Nitrogen fixation	-
17.	(Kumaresan et al. 2019)	2.07 eV	-	Environmental application	-
18.	(Zhang, Ke, and Yao 2018)	-	Stable	Pollutant degradation, hydrogen evolution	-
19.	(Hisatomi and Domen 2019)	2.36 eV	-	Water splitting	-
20.	(Pal et al. 2020)	2.1 eV	-	Production of hydrogen peroxide	-

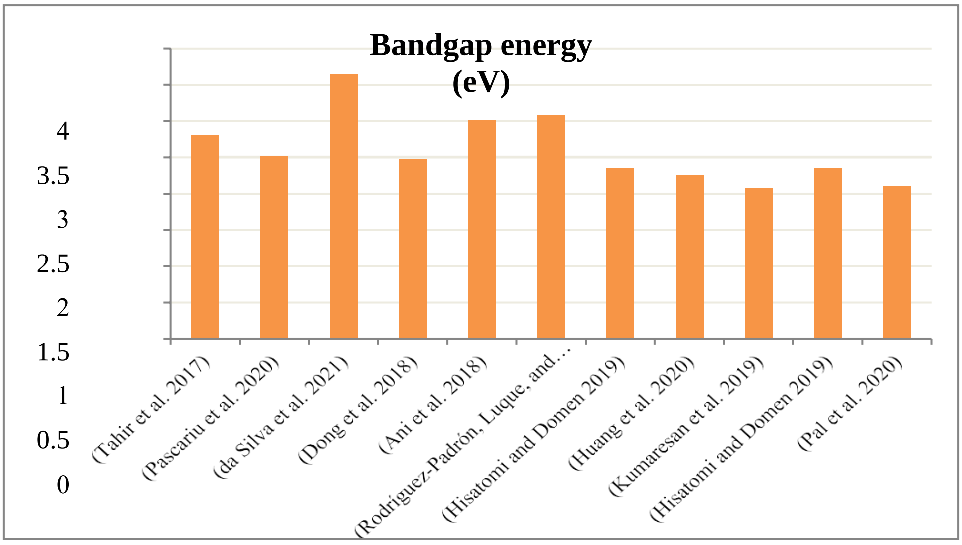

Fig.4 Comparison of bandgap energy

From the fig.4, it is found that the bandgap energy for the photocatalyst developed from the Agro-industrial waste achieves higher value compared to all other developments.

6. Discussion

According to the table, the TiO2 photocatalyst has a lot of potential in the field of photocatalysis for production of fuel and environmental remediation. The MoS2-based photocatalysts are attracting much attention because they have a good band gap for harvesting visible-light, creating it a favourable earth-abundant photocatalyst for environmental remediation, production of hydrogen, and for other applications. Carbonaceous materials have been shown to be crucial in the development and production of improved photocatalysts, and many carbonaceous photocatalysts are created.

The number of articles chosen for review from the research period from 2017 to 2021 is discussed below in table 3 and its graphical representation is illustrated in fig 3.

Table 3: Number of articles chosen for review

Year	Number of papers chosen for review
2017	2
2018	3
2019	7
2020	6
2021	2

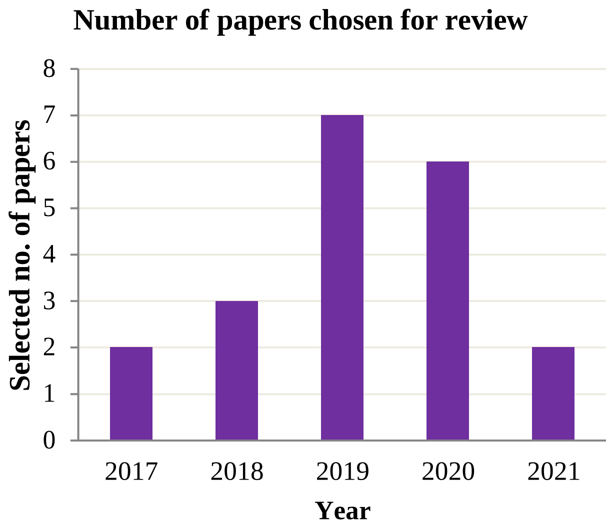

Fig.3 Number of papers chosen for the review

7. Conclusion

The present study takes the review of the existing researches on the design of photocatalysts and their applications in various sectors. Also, the opportunities and challenges for additional advancement of photocatalysts for good energy crises and environmental applications based upon the current advances in coordination chemistry and surface science is discussed. The good outcomes reveal that a further growth would progress and spread in various branches and in different directions.

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