CIÊNCIA e NATURA
ISSN 2179-460X
OPEN ACCESS
Ci. e Nat., Santa Maria, e84287, v. 47, 2025 • https://doi.org/10.5902/2179460X84287
Submitted: 29/06/2023 • Approved: 29/04/2025 • Published: 27/05/2025

Environment

Efficiency of both activated sludge system and its variations in removing the chemical oxygen demand from industrial waste: systematic review and meta-analysis

Eficiência de remoção de demanda química de oxigênio de efluentes industriais por sistema de lodos ativados e suas variantes: uma revisão sistemática e metanálise

Isabella Esper Tamburus[I], **Carlo José Freire de Oliveira**[I], **Wellington Francisco Rodrigues**[I], **Ana Carolina Borella Marfil Anhê**[I]

[I] Universidade Federal do Triângulo Mineiro, Uberaba, MG, Brazil

ABSTRACT

The activated sludge system is widely used worldwide to treat complex waste types, given its high efficiency level. The aim of the present study is to identify the efficiency of both activated sludge systems and their variations in removing the chemical oxygen demand (COD) from industrial waste, based on systematic review and meta-analysis. The search was carried out in Scopus and ScienceDirect databases; two independent researchers selected studies published between 2016 and 2020 to gather the data. The industrial waste types presented great initial COD variation, even within the same segments and typologies; furthermore, some activated sludge systems presented pre- or post-treatment. The systematic review and the meta-analysis allowed presenting the global efficiency of removal of chemical oxygen demand in industrial effluents by activated sludge systems and their variants used globally, which reaches 83.00% (CI = 82.00 to 93.00). In addition, the current study is the first on this topic; therefore, it will work as a reference for future studies addressing this subject.

Keywords: Biological processes; Liquid waste; Biological wastewater treatment

RESUMO

O sistema de lodos ativados é amplamente utilizado em todo o mundo para tratar tipos de resíduos complexos, devido ao seu alto nível de eficiência. O objetivo do presente estudo é identificar a eficiência de remoção de demanda química de oxigênio em efluentes industriais por sistemas de lodos ativados e suas variantes, através de uma revisão sistemática e metanálise. A busca foi realizada nas bases de dados Scopus e ScienceDirect; dois pesquisadores independentes selecionaram estudos publicados entre 2016 e 2020 para coletar os dados. Os tipos de resíduos industriais apresentaram grande variação inicial de DQO, mesmo dentro dos mesmos segmentos e tipologias; além disso, alguns sistemas de lodos ativados apresentaram pré ou pós-tratamento. A revisão sistemática e metanálise permitiram apresentar que a eficiência global de remoção da demanda química de oxigênio em efluentes industriais por sistemas de lodos ativados e suas variantes utilizados globalmente chega a 83,00% (IC = 82,00 a 93,00). Além disso, o presente estudo é o primeiro sobre esse tema; portanto, servirá de referência para futuros estudos sobre o assunto.

Palavras-chave: Processos biológicos; Resíduos líquidos; Tratamento biológico de águas residuais

1 INTRODUCTION

Environmental pollution triggers scientific and technological interests, mainly when it comes to issues related to river pollution, due to the inappropriate discharge of waste resulting from industrial processes (Freire et al., 2000; Zola et al., 2014; Shi et al., 2021).

Water contamination is one of the most critical pollution types, since it changes physical, chemical and biological water features and directly interfers with its quality and use for human consumption (Aguiar & Novaes, 2002; Garcia Torres et al., 2022).

It is necessary having mandatory control over the system used to properly treat waste, as well as understanding waste's toxic compounds during the purification process and analyzing the system's efficiency in removing toxic loads from it - it is often measured by reduced chemical oxygen demand (COD)[1], biochemical oxygen demand (BOD), toxicity or by other compounds whose removal is essential for proper waste final disposal (Araújo et al., 2005; Beal et al., 2006; Patoine et al., 1997; Santos et al., 2006; Ubay Çokgör et al., 1998).

Significant innovations have been observed in the biological wastewater treatment sector. These innovations aim at achieving higher treatment performance to meet the limits set to complex-waste discharge and easier solid/liquid separation (Van Haandel & Van Der Lubbe, 2012).

[1] The list of acronyms and their respective meanings present in this study are in Appendix G.

Treatments based on biological processes allow treating large waste volumes, having lower operation costs and simplifying operational procedures (Freire et al., 2000; Da Motta et al., 2003).

The biological treatment applied to waste, oftentimes, uses microorganisms that grow as flocculating aggregates in the suspended phase of aerated tanks. The traditional activated sludge (AS) process is an example of it; this process was developed in 1914 by Ardern and Lockett (Andern & Lockett, 1914) and is widely used to treat complex waste types, given its a high efficiency level (Jenkins et al., 2003).

Activated sludge is widely used as biological treatment to treat sanitary and industrial waste all around the globe, due to its great efficiency in removing BOD and COD, and to the fact that it demands small areas for its implementation. However, this system implies a more sophisticated operation and higher power consumption, including higher mechanization rates than other treatment systems (Bento et al., 2005; Von Sperling, 2012).

This system is basically supported by the biochemical oxidation of organic and inorganic compounds found in waste. It happens due to a diversified microbial population of bacterial, fungal, protozoan and micrometazoan species that remains suspended in aerobic medium (Bento et al., 2005; Davies, 2005).

According to Von Sperling (2012), there are several activated sludge process variations, and the main and most used ones are divided into those: “Regarding sludge age” - Modified aeration (less than 3 days), Conventional Activated Sludge (CAS) (4 to 10 days) and Prolonged Aeration (18 to 30 days); “Regarding flow” - Continuous flow (when waste gets in and out the activated sludge reactor; it is more often used for prolonged aeration) and Intermittent or batch flow (waste input is discontinuous in each activated sludge reactor); “Biological stage influent” - Raw sewage (often used in the prolonged aeration mode), Anaerobic reactor waste, Primary decanter waste (conventional activated sludge classic design) and Waste from other waste treatment process types (such as physical-chemical treatment or coarse biological filters for additional waste polishing).

Thus, if one takes into consideration the concern with industrial waste treatment efficiency and with activated sludge system relevance among biological treatment types, the aim of the present study was to identify the efficiency of both activated sludge systems and their variations in removing the chemical oxygen demand from industrial waste.

In addition to the great environmental relevance of the topic, this study presents itself as a reference for future studies and works on industrial effluent treatment, as well as on activated sludge, as it presents a compilation of essential information, new results and because there are no systematic review and meta-analysis studies in the bibliographic collection that address this topic and structure presented.

2 METHODS

The study protocol was registered on the Open Science Framework (OSF) platform, under registration number DOI 10.17605/OSF.IO/ZAHJG. It was structured based on recommendations in the Protocol known as Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) (Liberati et al., 2009).

2.1 Eligibility Criteria

It was important determining a current period of world landmark involved in the presented theme, since it is a global scale research. Therefore, studies published between 2016 and 2020 were selected, peer-reviewed and did not follow language restrictions, since a global pact was signed in September 2015, based on the 2030 Agenda (United Nations, 2015), according to which, efficient industrial waste use management must be linked to attainable and achievable Sustainable Development Goals (SDGs) (Patel et al., 2020).

The search for more sustainable technologies has been boosted, so that one could achieve energy recovery and reuse, as well as minimize the occurrence of secondary emissions, rather than just treating waste based on energy efficiency (Batstone et al., 2015). Thus, there are studies focused on assessing emerging wastewater technologies within the SDGs context in comparison to well-established ones, such as activated sludge systems, in order to adopt sustainable wastewater infrastructure (Munasinghe-Arachchige et al., 2020; Abyar et al., 2020; Delanka-Pedige et al., 2020).

Thus, the following studies were excluded: that did not report industrial waste treatment based on the activated sludge system, that did not address industrial waste, that did not present activated sludge system as, at least, one of the treatment steps, that did not present results of COD removal by activated sludge process and that aimed at removing specific substances from industrial waste.

2.2 Information sources and search strategy

Several previous studies were carried out to determine the study theme and question, as well as to assess the gray literature.

Descriptors were determined based on using Descriptors of Health Science (DeCS) and Medical Subject Headings (MeSH) platforms.

The selected descriptors were used as search strategy. The search was carried out on August 26, 2020, in the Scopus and ScienceDirect electronic databases, based on determining study period, on choosing order by relevance and on using the following structure: (“Activated sludge”) AND (“Industrial Effluent” OR “Industrial Waste”) AND (“Biological Oxygen Demand Analysis” OR “Biological Oxygen Demand” OR “Chemical Oxygen Demand”).

2.3 Selection of publications

Publication selection was carried out by two researchers; disagreements were solved by consensus.

Records were selected based on their titles and abstracts; duplicated publications were excluded from the review. Full text reading was applied to publications included in the review. Publications that have met the eligibility criteria were selected for the study and referred to Zotero software.

2.4 Data Extraction

Data from the selected studies were extracted and transferred to a standardized Microsoft Excel 2013 spreadsheet by two independent researchers; disagreements were solved by consensus.

The extracted data regarded authors, title, publication year, study location, waste type, industry type, initial COD, type of biotechnology treatment used and COD removal rate (efficiency).

2.5 Methodological quality assessment

Two independent researchers assessed the methodological quality of selected studies by adjusting them to the JBI Critical Assessment Tool for Prevalence Studies[2].

The assessed items were whether collections (P1), sample size (P2), and procedures and experiment descriptions were carried out properly (P3); whether data analysis was sufficiently performed (P4); and whether valid methods (P5) and statistical analysis (P6) were used. Each item included in the study was attributed scores ranging from zero to one point.

Divergent data were analyzed by observing tool elements to achieve greater accuracy and avoid bias. Studies that recorded score equal to six points were classified as of excellent quality, those recording score ranging from five to four points were of great quality, those recording score ranging from three to two points were of regular quality, and those recording score of one point were of poor quality. Excellent and great quality (four to six points) publications were included in the review.

[2] Available at: https://jbi.global/critical-appraisal-tools?fbclid=IwAR3FacyLiHDwqz4LD4qFu--8icYRSqes_SsNw6IqDNxr1HqmQTw8cWsBgXk.

2.6 Data Analysis

Data were tabulated in Microsoft® Excel; RStudio and Jamovi software (version 1.6.15) were used for data analysis and visual display. Absolute (N) or relative (%) frequencies were used for descriptive analysis, at 95% confidence level. Coefficient of variation, Skewness and Kurtosis were determined to describe distribution frequency. Chi-square goodness of fit test was used to associate the different assessed rates.

The general package for meta-analysis "meta" version 4.9-5 was used to assess associations between biotechnology treatments by using the "metaprop" command. Forest plot was used for data assessment and representation. Studies' heterogeneity was assessed in I^2 statistic, based on the Q statistic of the Cochran test and on the J number of the analyzed studies. Funnel chart was used to assess the presence of biases in the publications. Fixed and random effect models were used based on the data distribution set for each assessment (Agresti & Coull, 1998; Borenstein et al., 2010; Littell et al., 2008; Arango, 2001; Higgins et al., 2002).

3 RESULTS AND DISCUSSION

3.1 Selection of studies and methodological quality assessment

The present approach described and explored several reactors widely used at global scale (Table 1 - Appendix A).

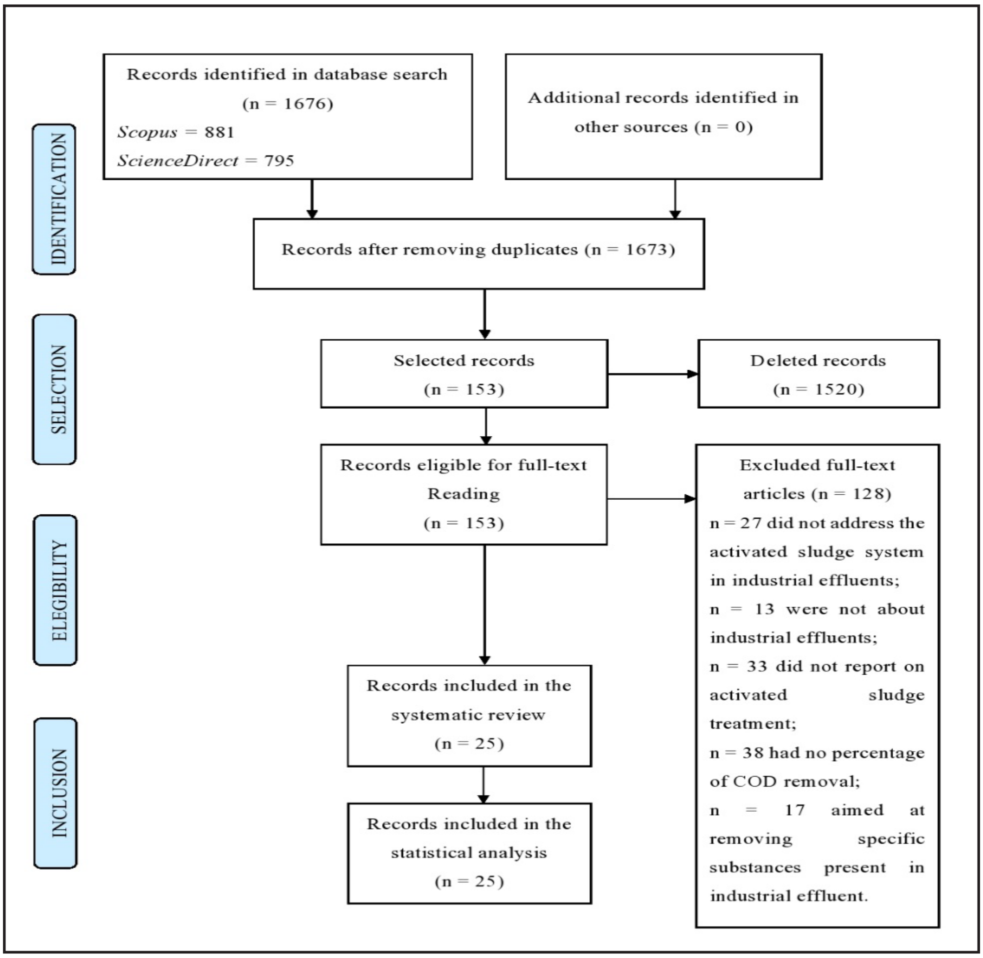
The search for studies that have identified the types of industrial waste efficiently treated by the activated sludge resulted in 1,676 articles - 3 of them were duplicates.

In total, 153 potential records were read in full after studies that did not meet the inclusion criteria were excluded from this review, based on reading their title and abstract.

Of these aforementioned totals, 27 did not address the activated sludge system adopted to treat industrial waste; 13 of them were not about industrial waste; 33 did not report the activated sludge treatment; 38 did not present COD removal rates; and 17 aimed at removing specific substances found in industrial waste.

In the end, 25 records were included in the systematic review (Figure 1); Table 2 (Appendix B) shows the methodological quality of eligible studies.

Figure 1 – Flowchart of the process of selecting records for systematic review



Source: Author (2022)

3.2 Characteristics of included studies

It was possible extracting the following data from all 25 included studies: authors, title, publication year, study location, waste type, industry type, initial COD, type of used biotechnology treatment and COD removal rate (efficiency).

In total, 16 of selected studies only used activated sludge biotechnology to treat waste, 7 used activated sludge as pre- or post-treatment, and 2 used activated sludge biotechnology and other technologies as treatment in order to compare technologies.

Thus, 18 studies showed activated sludge biotechnology efficiency and 2 of them also presented the efficiency of treatments that were not classified as activated sludge biotechnology, namely: Paździor et al., 2016; Wang et al., 2016.

In addition, 4 studies showed the efficiency of the used activated sludge system and its post-treatment efficiency (Insel et al., 2018; Solís et al., 2018; Sawadogo et al., 2018; Pitás et al., 2020); 1 study presented pre-treatment and total efficiency (Niwa et al., 2016); 1 study evidenced activated and total sludge system efficiency based on using pre-treatment (Chen et al., 2016); and 1 study showed total efficiency based on using post-treatment (Ahmadi et al., 2016).

Tables 3 and 4 (Appendix C) illustrate the main data extracted from the studies; authors, publication year, industrial typology, location, mean waste COD before treatment (mg.L^{-1}), biotechnology used in the treatment and mean COD removal from waste (treatment efficiency, in rates) in each eligible study.

Studies by Moore et al. (2016) and Cao et al. (2016) used Activated Carbon (PAC) followed by UV, Microfiltration (MF) followed by Reverse Osmosis (RO), as post-treatments, respectively. However, COD removal efficiency values were not shown in Table 4, as it does not apply to, and/or was not presented in, the study.

Noticeably, industrial waste showed large initial COD variation, even within the same segments and typologies.

Despite being food byproducts, brewery and oil mill waste showed wide initial COD variation when compared to each other. This finding was corroborated by Bakare et al. (2017), who have reported that brewery waste COD ranged from 2,000 to 6,000 mg.L^{-1}; and by Jaouad et al. (2020), who have shown that oil mill waste COD ranged from 80,000 to 200,000 mg.L^{-1}.

When one observes the initial COD interval recorded by Jaouad et al. (2020) and Değermenci et al. (2016) for oil mill waste, it is possible noticing that its difference is higher than 70,000 $mg.L^{-1}$.

There may be pre- or post–treatments, in addition to biological treatment, to increase the final quality of waste. Many advanced treatment technologies are applied to waste types that have recalcitrant pollutants from anthropogenic chemicals, such as pharmaceuticals, personal care products, pesticides, industrial chemicals, among others, and their degradation metabolites, like membrane separation, carbon adsorption and POAs (Snyder et al., 2007; Herrmann et al., 1993).

Membranes, as tertiary waste treatment technology, are widely used in the wastewater-reuse, pre-treatment desalination and membrane bioreactor fields (Tchobanoglous et al., 1998). Membrane modules can be coupled straight to conventional wastewater treatment processes, since they are easily integrated to existing wastewater treatments (Duan et al., 2016).

Overall, higher quality waste and better separation of it are achieved by using denser membranes, since they require higher operating pressure, such as NF and OR (Fritzmann et al., 2007). The significant advantage of NF processes over OR lies on the fact that they operate at lower pressure and do not lead to monovalent salt accumulation (e.g. NaCl) in the reactor - it damages bacteria responsible for the biological process (Choi et al., 2002).

POAs are also important to treat olive oil wastewater and other food and beverage waste types presenting high organic and nutrient content, since they achieve up to 99% treatment efficiency when they are used in combination to biological processes (Cañizares et al., 2007; Oller et al., 2011; Bustillo-Lecompte & Mehrvar, 2015).

3.2.1 Frequency analysis, prevalence of waste types and biotechnology treatments

The frequency of biotechnology treatment type was assessed among all possible methods found in the eligible studies (N = 39) (Table 5 - Appendix D). The highest frequency was observed for SBR: 12.82% (CI = 2.33 to 23.31), and it was followed by CAS, MBR, Two-stage MBR and SFD MBR: 7.69% (CI = -0.67 to 16.05); and Nanofiltration, SMBR and AS: 5.13% (CI = -1.79 to 12.05). Frequencies recorded for other treatment types reached 2.56% (CI = -2.40 to 7.52).

Prevalences followed the same distribution order and they pointed towards the prevalence of biotechnology treatment types among all applications described in this present study (N = 24), starting from 20.83% (CI = 4.58 to 37.08) recorded for SBR, which was followed by 12.50 % (CI = -0.73 to 25.73) recorded for CAS, MBR, Two-stage MBR and SFD MBR; by 8.33% (CI = -2.73 to 19.39) recorded for Nanofiltration, SMBR and AS; whereas other treatment types reached 4.17% (CI = -3.83 to 12.17).

Significant dependence on treatment type selections was evidenced (p = 0.02) by the analysis of cumulative frequency rate recorded for biotechnology treatment types in comparison to activated sludge treatment biotechnology groups addressed in this present study: MBR (0.43), SBR (0.25), CAS (0.14), AS (0.11) and MBBR (0.07).

Intervention frequency recorded for treatments applied to different waste types was assessed (N=39) (Table 5). Beverage waste (beer and soft drinks) accounted for the three highest frequencies observed during the analysis (15.38% - CI = 4.06 to 26.70); it was followed by mixed waste types (12.82% - CI = 2.33 to 23.31), as well as by olive oil and textile mills (10.26% - CI = 0.74 to 19.78).

Subsequently, winery, oil field, food (canned goods, milk, fruits and vegetables) and pharmaceutical products (general and opium) recorded 7.69% (CI = -0.67 to 16.05) frequency; other industrial typologies reached 2.56% (IC = -2.40 to 7.52). There was no association between the frequencies recorded for the assessed waste types, at global scale (p = 0.60).

The prevalences followed the same distribution order of distribution and indicated the prevalence of industrial typologies among all applications described in this present study (N = 15), starting from 40.00% (CI = 15.21 to 64.79) recorded for beverages (beer and soft drinks), which was followed by 33.33% (CI = 9.47 to 57.19) recorded for mixed waste types, 26.67% (CI = 4.29 to 49.05) recorded for olive oil and textile mills, 20.00% (CI = -0.24 to 40.24) recorded for wineries, potliferous fields, canned food, milk, fruits and vegetables) and pharmaceutical products (general and opium); other industrial typologies reached 6.67% (CI = -5.96 to 19.30).

The SBR system was the most frequent and prevalent biotechnology treatment type in comparison to other treatment types used in eligible studies.

The SBR system is widely used to degrade organic and nitrogenous compounds in industrial waste (Villaverde et al., 2000; Yalmaz & Öztürk, 2001). When it is compared to traditional or conventional treatments, one can observe a highly operational, flexible, easily obtainable (on time scale) technology applicable to newer and more varied pollutants (Popple et al., 2016; Dutta & Sarkar, 2015; Kulkarni, 2013).

SBR has several advantages, among them, lower operation and volume costs; good COD, nitrogen and phosphorus removal efficiency; great flexibility to combine nitrification and denitrification phases in a single reactor (Lim et al., 2011; Khan et al., 2017; Ding et al., 2011).

The MBR group was the most frequent in the cumulative rate recorded for biotechnology treatment type frequency in comparison to biotechnology treatment groups based on activated sludge. It is possible seeing that membrane bioreactors have gained great relevance to treat municipal and industrial waste types in recent years (Wang et al., 2016).

They have been increasingly used to treat wastewater, since it requires high treated-water quality (for its reuse) and limited implementation area (BCC Research, 2008). Nowadays, the MBR technology has been widely used to increase residual organic contaminant removal; furthermore, it presents the following advantages: adjustment to a wide range of influent fluctuation; achievement of good reduction in many Pharmaceuticals and Personal Care Products (PPCPs); it provides high quality waste free of microorganisms and suspended solids, and presents low organic matter concentration in comparison to CAS (Bui et al., 2016; Hai et al., 2011, Kimura et al., 2003 ; Luo et al., 2003 ; Luo et al. ., 2014).

Pulp and paper companies use the MBR treatment in combination to Reverse Osmosis (RO) to achieve near-total process-water recycling (water use reduction by 75%) (Johansson, 2012).

It is possible noticing that the industrial segment accounting for the highest frequency and prevalence in the included studies is related to the whole food and beverage industry, since it showed the three highest frequencies and prevalence of interventions set for treatments applied to different waste types.

Wastewater from the food industry contains large amounts of organic matter, such as fats, oils and suspended solids. Recent advances in wastewater treatment for the food industry have focused on improving the removal of organic matter and nutrients. As a result, traditional methods such as activated sludge processes have been widely used because they are economical and efficient in reducing BOD and COD (Yáñez-Hernández et al., 2024).

Yahi et al. (2014) reinforce that food industry wastewater presents high concentrations of organic materials. Thus, it is possible using biological treatment in waste. Biological treatment processes are widely used all around the planet; the aerobic process by activated sludge is the one mostly used among treatment processes classified as biological (Cunha et al., 2017); this finding justifies its broad use in this sector.

3.2.2 Analysis of territories found in the selected studies

Biotechnology treatment frequency was assessed among the possible methods found in the eligible studies (N = 38) (Table 6 - Appendix E). Thus, the highest frequency of the type of treatment biotechnology was observed for SBR: 13.16% (CI = 2.41 to 23.91); it was followed by CAS, MBR, Two-stage MBR: 7.89% (CI = -0.68 to 16.46); and by Nanofiltration, SMBR, AS and SFD MBR: 5.26% (CI = -1.84 to 12.36). Frequencies recorded for the other treatment types reached 2.63% (CI = -2.46 to 7.72) (p = 0.89).

Prevalences followed the same distribution order and they pointed towards the prevalence of biotechnology treatment types among all applications described in this present study (N = 24), starting from 20.83% (CI = 4.58 to 37.08) recorded for SBR, which was followed by 12.50 % (CI = -0.73 to 25.73) recorded for CAS, MBR, Two-stage MBR, and by 8.33% (CI = -2.73 to 19.39) recorded for Nanofiltration, SMBR, AS and SFD MBR; the other treatment types reached 4.17% (CI = -6.89 to 15.23) (p = 0.82).

Treatments' intervention frequency in different regions was also assessed (N = 38) (Table 6). Regions accounting for the three highest analysis frequencies were China, with 15.79% (CI = 4.2 to 27.38); Turkey, with 10.53% (CI = 0.77 to 20.29); and Brazil, Iran, Morocco, Western Africa, with 7.89% (CI = -0.68 to 16.46). Subsequently, Poland, Portugal, Hungary, Singapore and India showed 5.26% frequency (CI= -1.84 to 12.36); the remaining ones reached 2.63% (CI= -2.46 to 7.72) (p = 0.67).

Prevalences followed the same distribution order and they pointed towards the prevalence of regions among all those described in this present study (N = 17), starting from 35.29% (CI = 12.57 to 58.01) recorded for China, which was followed by 23.53% (CI = 3.37 to 43.69) recorded for Turkey; by 17.65% (IC = -0.47 to 35.77) recorded for Brazil, Iran, Morocco, Western Africa; by 11.76% (IC = -3.55 to 07.27) recorded for Poland, Portugal, Hungary, Singapore and India; the other regions reached 5.88% (CI = -5.30 to 17.06) (p=0.67).

The SBR system was the most frequent and prevalent biotechnology treatment applied in different regions assessed by the eligible studies. The SBR is a versatile and efficient treatment for wastewater, offering advantages such as enhanced nutrient removal efficiency, adaptability to fluctuating influent characteristics and reduced footprint (Ugwuanyi et al*., 2024)*.

This finding can be explained by the fact that biological treatments based on activated sludge in sequencing batch reactors are widely used to treat industrial waste, as they have system feeding flexibility, versatility and cost-effectiveness in comparison to other biological-treatment biotechnologies (Liu et al., 2018; Yusoff et al., 2016; Monsalvo et al., 2009; Mena et al., 2019).

SBRs have been efficient in degrading phenols and chlorophenols, herbicides, coke wastewater and pharmaceutical wastewater (Mena et al., 2019; Monsalvo et al., 2009; Sanchis et al., 2014; Marañón et al., 2014; Marañón et al., 2009; Sanchis et al., 2014; Marañón et al. al., 2008; Abu Hasan et al., 2016), among others. These nutrients are easily removed, because their microorganisms are tolerant to toxic compounds and environments, in addition to be able to adjust microbial populations to specific pollutants (Liu et al., 2018; Yusoff et al., 2016; Monsalvo et al., 2009; Mena et al., 2019).

In addition, China was the most frequent and prevalent region among the ones assessed in the eligible studies. This finding is assumingly correlated to the fact that industry types located in China generate waste types that reach good efficiency rates when it treated in activated sludge systems. Coke waste for example, is produced in more than 560 manufacturing facilities worldwide, and approximately 400 of them are located in China; 59 operate in Europe (Kwiecinska et al., 2017).

China has become the world's largest paper and cardboard producer. In 2014, there were approximately 3,000 papermaking companies in China; altogether, they produced 0.1 billion tons of paper and cardboard, which accounted for 25% of the world's total paper and cardboard production (Yu et al., 2016).

However, since the early 1990s, research institutions in China have initiated cash reward policies for publication. According to these policies, students can get cash back from each eligible publication (Sun & Zhang, 2010; Wang, 2016). This is a good strategy to encourage journal–article production and to justify the result found in this present study.

Furthermore, Chinese universities play predominant role in scientific research production in China; they contribute with 82.8% of dissertations and with 73.4% of journal articles - 83.0% of them are indexed in the Web of Sciences (National Bureau of Statistics of China, 2015).

The frequency of studies related to waste treatments based on using different biotechnologies was assessed to found distributions between continents and countries. It was possible observing heterogeneous distribution according to CV (continent = 68.85%, countries = 55.00%), Skewness (continent = 0.46, countries = 1.08) and Kurtosis (continent = -0.82, countries = -0.70).

Absolute distribution of continents was 0.04 (Oceania), 0.14 (Africa and America), 0.28 (Europe) and 0.39 (Asia); it was possible observing close association among rates in comparison to continents (p = 0.03) (Table 7) (Appendix F).

This finding can be correlated to disparity in scientific production between nations (Ciocca; Delgado, 2017).

3.2.3 Meta-analysis applied to the selected studies

Figure 2 presents the meta-analysis applied to CAS and AS biotechnology treatments' COD removal efficiency. According to a) and b), CAS results were assessed and they reached mean efficiency of 76.20% (CI = 48.48 to 45.47); however, if winery waste is removed from this assessment, efficiency rises up to 87.54% (CI = 82.53 to 91.83), and presents no heterogeneity (I^2 = 0%).

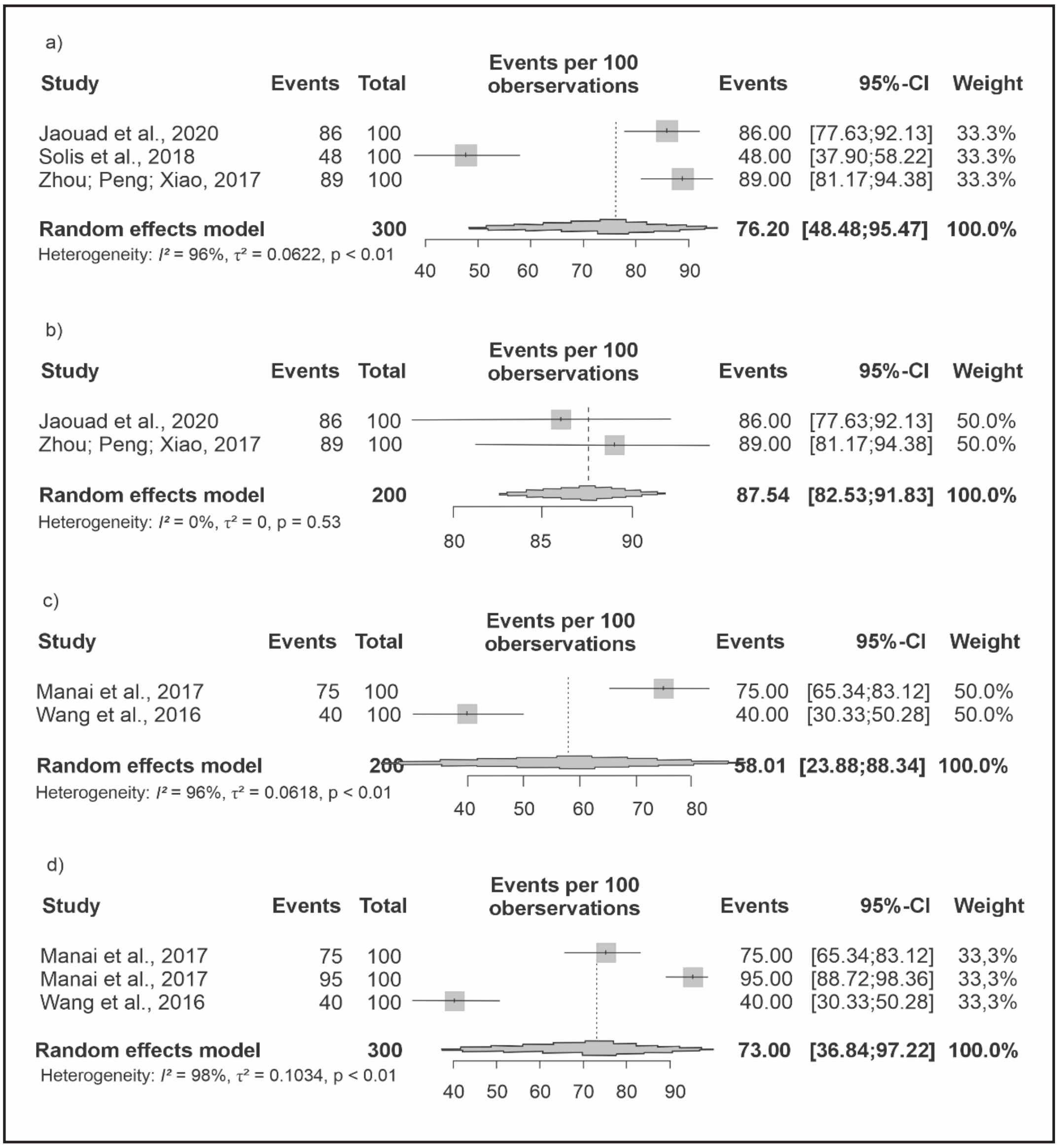
This finding means that there may be risk of bias or of waste type influence on efficiency. However, the data indicated that, probably, it is the type of effluent that influences the variability, since in the methodological quality analysis of the study that evaluated the effluent from the winery, the maximum score was obtained.

According to c) and d), results were assessed and showed mean efficiency of 58.01% (CI = 23.88 to 88.34). However, when the efficiency recorded for the AS treatment added with enzymes was taken into consideration, it increased to 73.00% (CI = 36.84 to 97.22).

Immobilized microorganisms and bioaugmentation processes have been assessed in order find ways to increase biological system's efficiency (Keskes et al., 2013). Bioaugmentation process efficiency is correlated to several factors, such as pollutant concentration, and bioaugmented microorganisms' chemical property and activity (Djelal & Amrane, 2013; Rodríguez-Rodríguez et al., 2012).

Both assessments (in c) and d)) showed high heterogeneity: I^2 = 96% and I^2 = 98%, respectively. It is so, because, in addition to the waste type influencing variability, different techniques (i.e., enzymes) were also used.

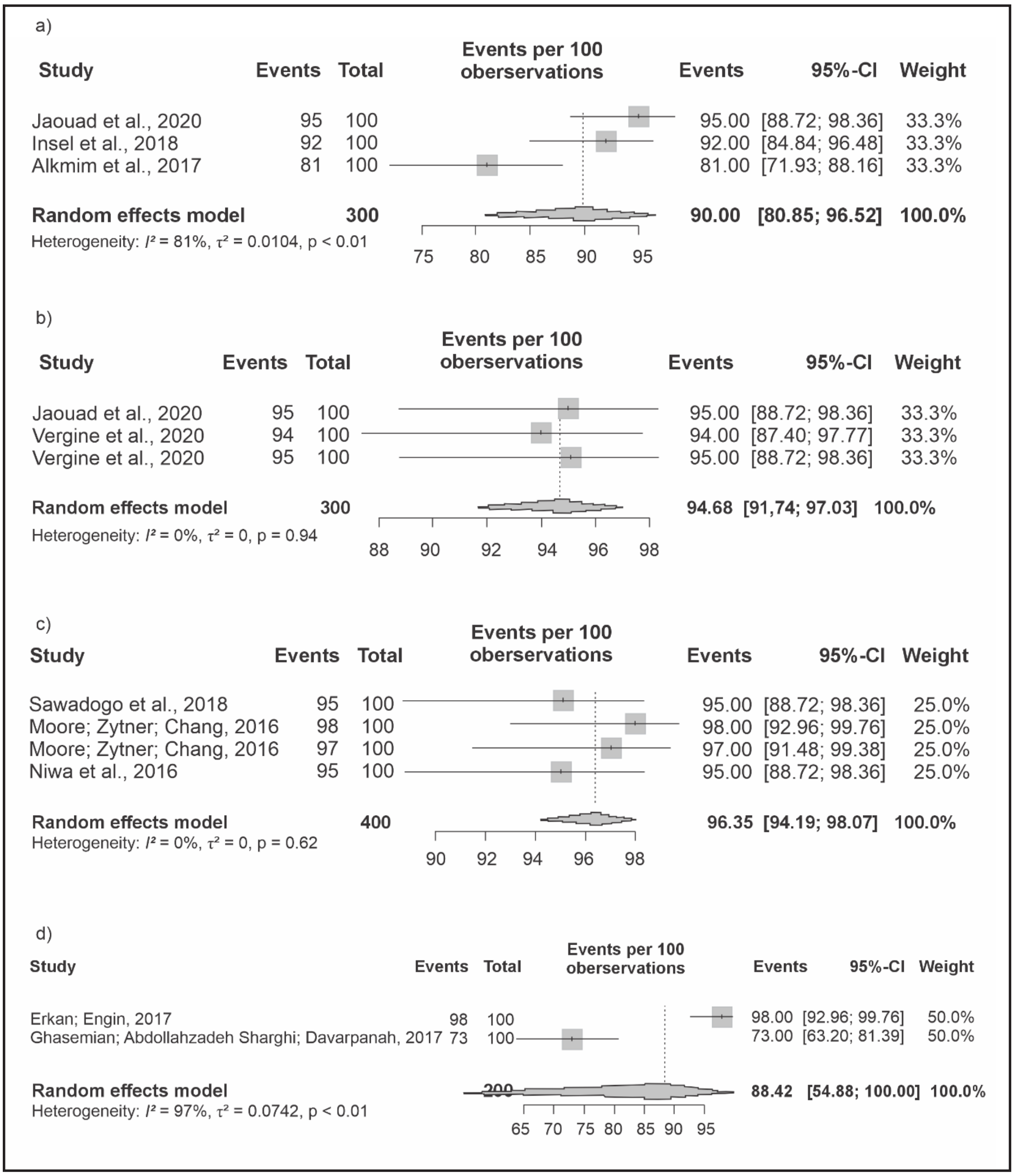
Figure 2 – Meta-analysis assessment of COD removal efficiencies of CAS and AS treatment biotechnologies



Source: Author (2022). Legend: (a) CAS – with winery (Solis et al., 2018); (b) CAS – without winery (Solis et al., 2018); (c) AS; (d) AS (with addition of enzymes – Manai = 95)

Figure 3 shows the meta-analysis applied to the COD removal efficiency of MBR, SFD MBR, Two-stage MBR and SMBR biotechnology treatments.

Figure 3 – Evaluation by meta-analysis of the COD removal efficiencies of MBR, SFD MBR, Two-stage MBR and SMBR treatment biotechnologies



Source: Author (2022). Legend: (a) MBR (the refinery for oil increases dispersion = 81); b) SFD MBR; c) Two-stage MBR d) SMBR

MBR (a)) recorded mean efficiency of 90.00% (CI = 80.85 to 96.52); the study by Alkmim et al. (2017) dealt with oil refinery waste and found increased dispersion (I^2 = 81%).

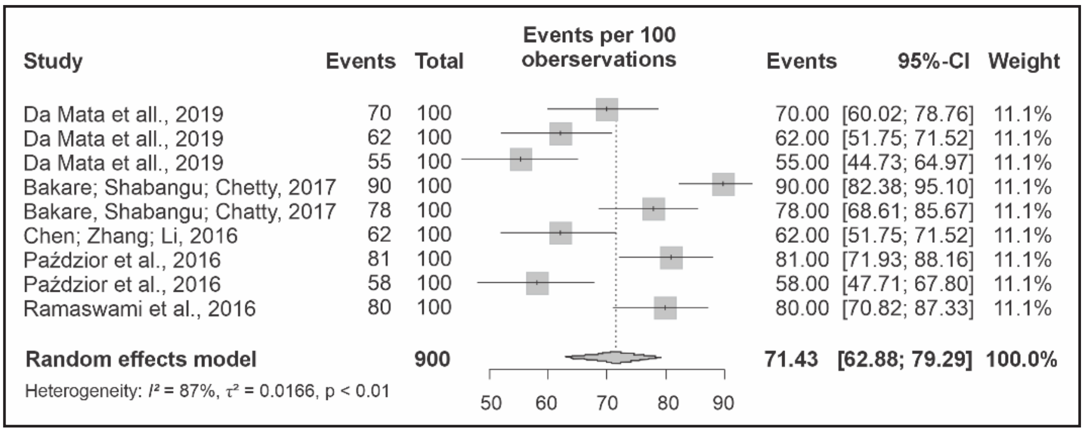
Alkmim et al. (2017) presented the farthest efficiency from the mean. This outcome may have occurred because petroleum waste contains a wide variety of organic and inorganic pollutants, including sulfites, ammonia, cyanides, aliphatic hydrocarbons, as well as polyaromatic hydrocarbons such as ethylbenzene, toluene, benzene and 1-methylethylbenzene, besides phenolic compounds (Wake, 2005). This feature may represent greater difficulty to degrade these compounds in biological systems.

No dispersion was observed for SFD, MBR and for the Two-stage MBR (b)) and (c)) (I^2 = 0%). Mean efficiencies reached 94.68% (CI = 91.74 to 97.03) and 96.35 % (CI = 94.19 to 98.07), respectively. Niwa et al. (2016) only presented pre-treatment and total efficiency (Table 4) to perform the Two-stage MBR meta-analysis. It was necessary calculating this system's COD removal rate by using study data ($mg.L^{-1}$) and the model proposed by Von Sperling (2014).

SMBR (d)) recorded mean efficiency of 88.42% (IC = 54.88 to 100.00) and high heterogeneity (I^2 = 97%) due to the influence of different waste types.

Figure 4 shows the meta-analysis applied to SBR efficiency in removing COD; it resulted in 71.43% (CI = 62.88 to 79.29) and I^2 = 87%, due to influence of different waste types.

Figure 4 – Evaluation by meta-analysis of the efficiency of COD removal by SBR



Source: Author (2022)

The highest mean efficiency recorded for the Two-stage MBR (96.35% - CI = 94.19 to 98.07) was observed after this meta-analysis assessed the efficiency of some biotechnology treatments found in the selected studies to remove COD.

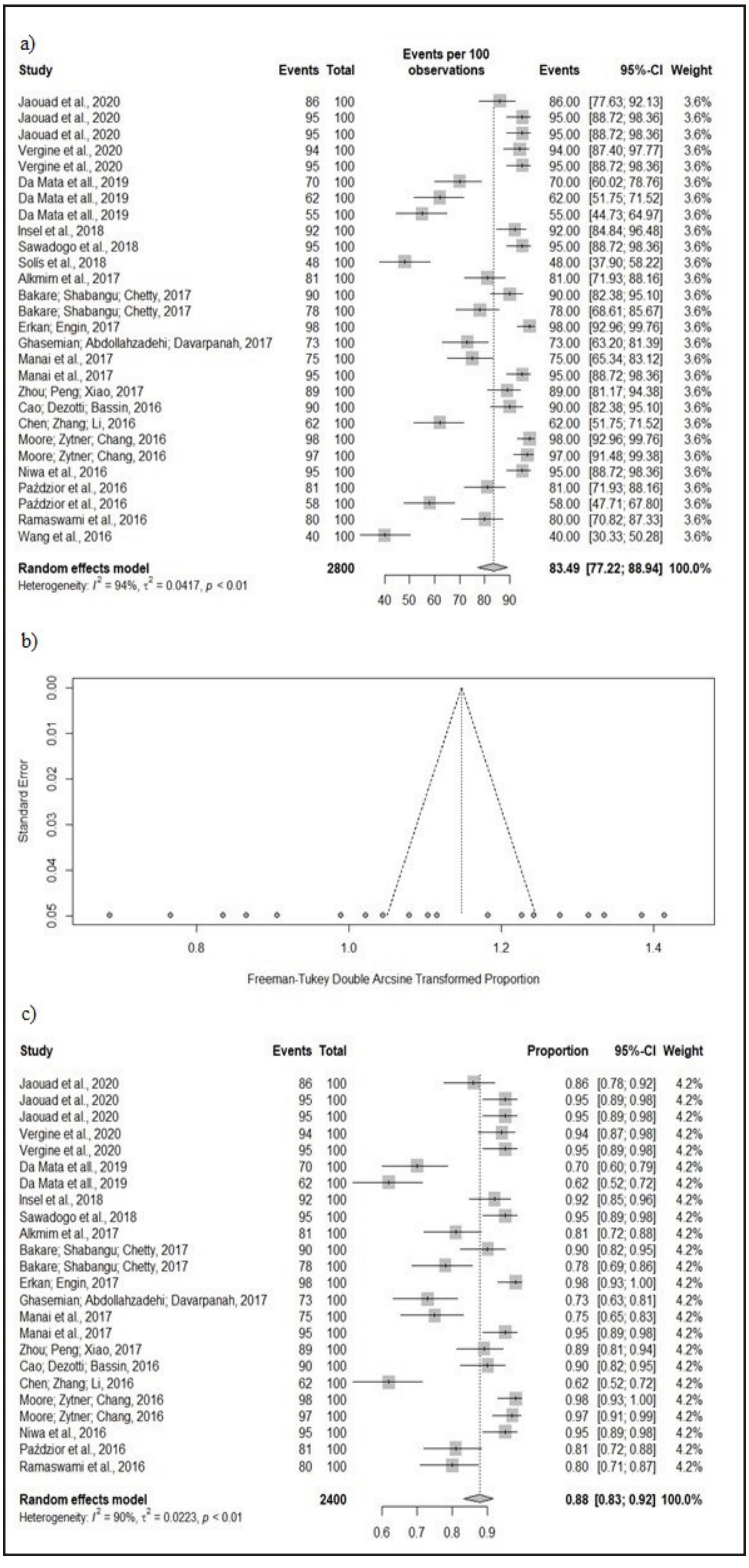
MBR has advantages such as superior effluent quality, reduced sludge production and compact footprint compared to conventional activated sludge systems (Rahman et al., 2023).

In recent decades, MBRs have received significant relevance due to being a technology that presents competitive advantages in terms of excellent process performance and complete biomass separation under activated sludge treatment in comparison to high technologies. High performance and process stability features allow maximum compatibility and easy integration to post-treatment and resource recovery alternatives (Cokgor et al., 2009). MBR has great ability to remove different contaminant types, including phenolic compounds (Baresel et al., 2019).

In addition, nitrifying bacteria (slow growing microorganisms) can be enriched in this complete-retention system, and achieve high and stable nitrification efficiency. Efficient biological nitrogen removal can be achieved when MBR is integrated to anoxic zones (Li et al., 2006; Rosenberger et al., 2002; Tan et al., 2008). MBRs/anoxic-oxic processes integration carried out to increase organics and nutrients' removal has been very successful (Iorhemen et al., 2017; Neoh et al., 2016; Meng et al., 2017).

High heterogeneity (I^2 = 94%) in data distribution was initially verified in assessments of global estimates for the efficiency of different biotechnology treatments applied to different waste types that are evaluated worldwide (Figure 5 a). Data were transformed into the Neperian log scale in order to find more consistent estimates; however, in addition to high heterogeneity, this transformation overestimated the efficiency recorded for the treatments (98.00%, data not shown).

Figure 5 – Definition of the global average efficiency of COD removal of the treatment biotechnologies of the eligible studies



Source: Author (2022). Legend: (a) Distribution of data to verify the global efficiency of the treatment biotechnologies of the eligible studies; (b) sensitivity analysis of risk of bias; (c) Distribution of data with the final global efficiency of the treatment biotechnologies of the eligible studies

The sensitivity analysis of bias risk (Figure 5 b) allowed identifying four assessments that have reduced the effect of global efficiency estimates, which were removed to carry out a new analysis. This removal was not closely associated with bias risk, since the respective methodological quality analyses applied to both studies met the eligibility criteria; however, waste and techniques variability embodied critical role in heterogeneity results.

Thus, the second analysis (Figure 5 c) enabled identifying a more consistent global estimate (83.00% - CI = 82.00 to 93.00) of the efficiency recorded for biotechnologies applied to waste treatments, worldwide.

This good global efficiency may explain the fact that activated sludge treatment systems have been used in several industrial waste types, since they are the most widely used biological wastewater treatment process developed for domestic and industrial waste in the world (Orhon, 2015; Li et al., 2019; Ren et al., 2018; Zeng et al., 2018; Chisti, 1998; Gray, 1990; Moo-Young & Chisti, 1994; Singleton, 1994).

3.3 Study gaps

In the present study, it was possible to evaluate several results through eligible studies, such as the most frequent and prevalent types of industrial effluents destined for treatment by activated sludge systems worldwide. The high efficiency of activated sludge systems was observed through global efficiency. Also, the data also allowed us to observe that the efficiency relationship between the adopted biotechnology and the effluents should be better explored in new primary studies to generate more variability in the treatment and types of effluents and, consequently, more consistent responses regarding the individual efficiencies of treatment biotechnologies.

Therefore, more primary studies are needed (all biotechnologies have not yet been tested in all effluents types found in the selected studies) to assess the application of greater biotechnology treatment variability to more effluent's types. In other words, it is necessary to take into consideration effluents types at the time to determine the efficiency of different biotechnology types; however, the bibliographic collection is a limitation.

The discussion to compare the present study to similar ones was difficult, since the current research was pioneer in addressing this topic. Thus, the present study will work as reference for future studies addressing this subject.

4 CONCLUSION

The current study will work as reference for future studies addressing this subject, since it was the first to assess this matter.

The systematic review and the meta-analysis allowed presenting the global efficiency of removal of chemical oxygen demand in industrial effluents by activated sludge systems and their variants used globally reaches 83.00% (CI = 82.00 to 93.00).

In addition, the highest biotechnology frequency and prevalence rates among the analyzed methods were recorded for Sequential Batch Reactor (SBR), which reached 12.82% (CI = 2.33 to 23.31) and 20.83% (CI = 4.58 to 08.37), respectively.

With respect to the analysis applied to cumulative frequency rates of biotechnology treatment types in comparison to biotechnology treatment types based on activated sludge one can state: firstly, that the Membrane Bioreactor (MBR) group (0.43) - followed by the SBR group (0.25) - showed significant dependence differences in treatment type selections ($p = 0.02$).

Waste presenting the highest frequency and prevalence of analyses, among the assessed typologies was beverages (beer and soft drinks): 15.38% (CI = 4.06 to 26.70) and 40.00% (CI = 15.21 to 64.79), respectively.

SBR was the most frequent and prevalent biotechnology treatment in the study regions: 13.16% (CI = 2.41 to 23.91) and 20.83% (CI = 4.58 to 37.08), respectively.

China recorded the highest analysis frequency and prevalence in eligible studies: 15.79% (CI = 4.2 to 27.38) and 35.29% (CI = 12.57 to 58.01), respectively. It was possible observing heterogeneous distribution in analysis of the frequency of studies related to waste treatment based on using different biotechnologies applicable for distributions between continents and countries. Absolute frequency distribution rates in studies on continents were 0.04 (Oceania), 0.14 (Africa and America), 0.28 (Europe) and 0.39 (Asia) - there was close association among rates when it came to continents ($p = 0.03$).

And the meta-analysis allowed identifying the biotechnology treatment accounting for the highest mean COD removal efficiency, namely: Two-stage MBR (96.35% - CI = 94.19 to 98.07).

ACKNOWLEDGEMENTS

The authors acknowledge the financial and institutional support of Improvement of Higher Education Personnel (CAPES), the Federal University of Mineiro Triangle (UFTM), the National Council for Scientific and Technological Development (CNPq) and the Minas Gerais State Research Support Foundation (FAPEMIG) (RED-00224-23).

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Authorship contributions

1 – Isabella Esper Tamburus

Degree in Environmental Engineering from the Federal University of Triângulo Mineiro
https://orcid.org/0000-0002-9329-0347 • isabelaesper@hotmail.com
Contribution: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing – review & editing

2 - Carlo José Freire de Oliveira

PhD in Basic and Applied Immunology from the University of São Paulo
https://orcid.org/0000-0003-2211-7333 • oliveiracjf@gmail.com
Contribution: Resources, Writing - review & editing

3 – Wellington Francisco Rodrigues

PhD in Health Sciences from the Federal University of Triângulo Mineiro.
https://orcid.org/0000-0002-3426-2186 • wellington.frodrigues60001@gmail.com
Contribution: Data curation, Formal analysis, Methodology, Software, Visualization, Writing - review & editing

4 – Ana Carolina Borella Marfil Anhê

PhD in Health Sciences from the Oswaldo Cruz Foundation
https://orcid.org/0000-0002-6970-2479 • ana.anhe@uftm.edu.br
Contribution: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Visualization, Writing - review & editing

How to quote this article

Tamburus, I. E., Oliveira, C. J. F., Rodrigues, W. F., & Anhê, A. C. B. M. (2025). Efficiency of both activated sludge system and its variations in removing the chemical oxygen demand from industrial waste: systematic review and meta-analysis. *Ciencia e Natura*, 47, e84287. DOI: https://doi.org/10.5902/2179460X84287. Available in: https://doi.org/10.5902/2179460X84287