www.gi.sanu.ac.rs, www.doiserbia.nb.rs
J. Geogr. Inst. Cvijic. 2024, 74(1), pp. 17–28

Original scientific paper

UDC: 911.2:574.9(2)
https://doi.org/10.2298/IJGI2401017S

Received: December 11, 2023
Reviewed: February 5, 2024
Accepted: March 25, 2024

THE COMPARISON BETWEEN DIFFERENT TYPES OF CONSTRUCTED WETLANDS FOR BIOCHEMICAL OXYGEN DEMAND REMOVAL EFFICIENCY

Nikola Stanković[1] *

[1]Electric Power of Serbia Joint-Stock Company, Belgrade, Serbia; e-mail: seki.stankovic@gmail.com

Abstract: This research shows efficiency of constructed wetlands (CWs) to purify waste water in the case of Biochemical Oxygen Demand (BOD). CWs such as surface flow (SF), subsurface flow (SSF), and hybrid (HYB) systems have been compared to provide an analysis about which system has better performance for BOD removal efficiency. Data were collected from different scientific articles and from all over the world. Meta-analysis technique was employed to aggregate data from scientific sources, facilitating hypothesis testing, and comparisons between different types of CWs. All the systems of CWs show satisfactory removal efficiency. HYB systems are shown to be the most efficient. One-way analysis of variance (ANOVA) has been applied to analyze differences between respective CWs using R software. It shows that there is a statistically significant difference between different types of CWs. Post-hoc Tukey's Honestly Significant Different (HSD) analysis demonstrates a statistically significant difference between SF and HYB systems in the case of BOD removal efficiency. Also, Post-hoc Tukey's HSD shows statistically significant difference between SSF and SF CWs. On the other hand, Post-hoc Tukey's HSD does not show statistically significant difference between HYB and SSF CWs. The significant reduction rates for BOD removal efficiency, demonstrates that CWs can be used to diminish this kind of pollution.

Keywords: constructed wetlands; removal efficiency; biochemical oxygen demand; One-way analysis of variance

1. Introduction

The assessment of Biochemical Oxygen Demand (BOD) has long served as the fundamental method for gauging water pollution levels (Hach et al., 1997). It stands as the paramount metric in the operational framework of sewage treatment facilities. By comparing BOD levels in the raw sewage entering the treatment plant with those in the treated effluent discharged from the facility, it can evaluate the efficiency of the plant. For instance, in a typical urban setting, untreated sewage generally carries a BOD concentration of approximately 300 mg/L. If the effluent from a wastewater treatment plant shows a BOD level of approximately 30 mg/L, it indicates that the plant has successfully eliminated 90% of the BOD content (Hach et al., 1997). BOD stands as one of the foremost parameters utilized in evaluating water quality. It furnishes

*Corresponding author, e-mail: seki.stankovic@gmail.com

insights into the readily biodegradable segment of organic matter present in water (Jouanneau et al., 2013). When examining the sequential progression of pollutant removal needs in developing nations, emphasis should initially be placed on the elimination of organic substances like BOD and Chemical Oxygen Demand (COD; Von Sperling & Platzer, 2019). The primary reason for decreased levels of dissolved oxygen in water stems from the presence of waste materials that deplete oxygen. In order to determine the presence of these pollutants, the BOD analysis can be applied (Abdullahi et al., 2020). The BOD method stands out as the most frequently employed approach for quantifying the presence of organic materials that consume oxygen (Shmeis, 2018). The BOD test is utilized to evaluate the effectiveness of waste water treatment and serves as a vital environmental metric for determining the oxygen need of wastewater, effluents, and contaminated water (R. Kumar & A. Kumar, 2005). In Serbia, BOD is included as a parameter for excellent ecological status, the first class of surface water, as well as for the second class of surface water, which is not the case with COD (Uredba o graničnim vrednostima zagađujućih materija u površinskim i podzemnim vodama i podzemnim vodama i sedimentu i rokovima za njihovo dostizanje, 50/2012).

Based on the Statistical Office of the European Union (Eurostat), BOD is included in the Sustainable Development Goals (SDG) indicator set (United Nations, n.d.). It is employed to track advancements toward achieving SDG 6 concerning clean water and sanitation, as well as SDG 15 concerning the protection, restoration, and sustainable utilization of land (United Nations, n.d.). These goals are integrated into the European Commission's priorities as part of the "European Green Deal" (European Commission, n.d.). Furthermore, it is stated that rivers with the lowest pollution levels typically exhibit BOD values below 1 mg O_2/L, while moderately and heavily polluted rivers tend to have values ranging from 2 to 8 mg O_2/L (Eurostat, n.d.).

BOD removal efficiency in CWs ranges from 67% to 95%, with a mean of 78%, as reported by Perez et al. (2023), while it was specifically noted to be 95% in the study by Qin and Chen (2016). According to the study by Gabr et al. (2023), it was discerned that horizontal subsurface flow (SSF) systems achieved a BOD removal efficiency of 78.2%, with vertical flow (VF) CWs exhibiting a BOD removal efficiency of 75%, culminating in an overall efficiency of 96.7% for BOD, emphasizing the effectiveness of CWs. Mentioned percentages underscore the variability in BOD removal rates, offering valuable insights into the efficiency of CWs, as a pivotal parameter for evaluating CWs wastewater treatment performance. Additionally, BOD plays a crucial role in the sizing of CWs (Nurmahomed et al., 2022). Wetland treatment systems were developed to enhance water quality and utilize the biodegradation capacity of plants (Shutes, 2001). Treatment of wetlands prove highly effective in addressing these requirements (Von Sperling & Platzer, 2019). They are manmade systems using benefit of the processes which are occurring in natural wetlands by entailing vegetation, soil, and accompanied microbial activity to treat waste water (Vymazal, 2005).

Today, methods of CWs have found wide use in Europe, primarily in Germany, Denmark, Italy, the Netherlands, Czech Republic, France, Slovenia, and so on (Vymazal, 2009). The adoption and spread of this technology are rapidly increasing in Denmark, Germany, and the United Kingdom, with tens of thousands of installations worldwide (Mulkeen et al., 2023). As a plant, *Phragmites australis* (common reed) is used, but other wetland species mainly macrophytes such as *Phalaris arundinacea* (reed canarygrass), *Typha latifolia* (cattails), *Typha Angustifolia* (narrowleaf cattail), *Pistia Stratiotes* (water lettuce), *Schoenoplectus lacustris* (common bulrush), *Glyceria maxima* (sweet mannagrass), *Hydrilla verticillate* (water thyme), *Nelumbo nucifera* (sacred lotus), *Eichhornia crassipes* (water hyacinth), and *Eleocharis dulcis* (Chinese water chestnut) can be found (Brix, 1994; Haydar et al., 2020; Prihatini et al., 2017; Prihatini et al., 2023; Prihatini & Soemarno, 2023).

Currently, there are several types of CWs which are used for waste water treatment. One of the classifications of CWs is made by the wetland hydrology (Vymazal, 2005). Therefore, it is possible to differentiate between free water SF, CWs, and SSF system. In the SSF system there are horizontal flow (HF) and, due to the substantial need to remove ammonia, the development and use of VF CWs commenced (Vymazal, 2005). There is also HYB CWs which are usually a combination of the HF and VF. The VF CW is regarded as a highly aerobic system characterized by elevated redox potentials that promote aerobic microbial activities (Knight et al., 2000). These systems are used in order to achieve better treatment effects. In this study, the BOD removal efficiency of different types of CWs has been investigated. Based on the all the previously mentioned about the BOD, that serves as one of the parameters for water quality, efficiency of waste water treatment by CWs and as a crucial factor in determining the size of a CWs, this indicator was chosen.

The aim of this work is to analyze how good CWs are in the process of BOD removal efficiency. By using Meta-analysis, data from other studies have been collected in order to test hypotheses, provide final results about the efficiency and comparison between CWs. One of the objectives was focused on the comparison of different types of CWs to purify waste water. In this case, organic pollution and its indicator BOD has been explored. Therefore, the final goal was to find out which type of CWs has better performance and this was done by statistical comparison. This paper, in comparison with other articles, shows a new approach for summarizing data from different scientific articles in order to test which CW has better performance in removing BOD, demonstrating a statistically significant difference between various systems by using ANOVA and Post-hoc Tukey's HSD. Therefore, at the outset of the research, the following hypotheses were formulated:

- (H_0): Various types of CWs do not act differently in the case of BOD removal efficiency; and
- (H_1): HYB CWs are supposed to be better systems for waste water purification in the case of BOD removal efficiency than other systems.

2. Materials and method

In order to explore the given research objectives and at the same to have clear pathway of research, one type of CW will be prioritized. HYB CWs have been introduced in order to enhance BOD removal efficiency. This system will be only the basis and benchmark for the comparison with other systems. The method which has been used in this study is based on the quantitative summary and Meta-analysis of removal efficiency for different types of CWs. Meta-analysis was adjusted to outline experimental behavioral, medical, and social sciences evidence (Hu et al., 2023). The data which are used for this research have been collected from different sources for the period from 1996 to 2023 (Table 1). They have been collected based on the types of CWs and a response parameter such as BOD. Average values for the response parameter were gathered, while data showing negative removal efficiency were excluded from the analysis.

Table 1. Data sources collected from 1996 to 2023

References/Constructed wetland and parameter	SF	BOD	SSF	BOD	HYB	BOD
Kadlec & Knight (1996)	+	+	+	+	+	+
R. Shrestha & P. Shrestha (2000)	–	–	–	–	+	+
Vymazal (2001)	+	-	+	–	+	+
Cooper (2001)	–	–	–	–	+	+
Vymazal (2005)	–	–	–	–	+	+
Paing & Voisin (2005)	–	–	+	+	–	–
Kato et al. (2006)	–	–	–	–	+	+
Vymazal & Kröpfelova (2008)	+	+	+	+	+	+
Vymazal (2009)	–	–	+	+	–	–
Abdelhakeem et al. (2016)	–	–	+	+	–	–
Prihatini et al. (2017)	+	+	–	–	–	–
Thalla et al. (2019)	–	–	–	–	+	+
Haydar et al. (2020)	–	–	–	–	+	+
Lokesh et al. (2023)	–	–	+	+	–	–
Didanovic & Vrhovsek (2023)	–	–	+	+	–	–
Gabr et al. (2023)	–	–	+	+	–	–
Perez et al. (2024)	–	–	+	+	–	–

Note. (+) indicates present of data and (–) indicates non-present. SF − surface flow; SSF − subsurface flow; HYB – hybrid; BOD − biochemical oxygen demand.

Three types of CWs have been included: free water surface CWs with emergent macrophytes, SSF CWs (HF and VF), and HYB systems. The data for the HF and VF CWs have been merged in one group as SSF CWs. The data for the VF CWs are not separated from the HF data because of the lack of data for this system and due to the unavailability of information about which type of SSF CW is presented in publications. By trying to find the data in different electronic browsers, typical words have been applied. These words are: constructed wetlands, performance of constructed wetlands, types of constructed wetlands, use of constructed wetlands, etc. Open online sources which have been used are: Web of Science, ScienceDirect, Wiley online library, Springer Link, Mendley. In addition, all electronic sources and literature which are available in the libraries of the University of Bayreuth have been explored. Therefore, data which have been published in books, articles, or other publications have been employed in this research. The software which was used for statistical analysis of the data is R (version 4.3.0). In order to test hypotheses, as a statistical method, ANOVA with Post-hoc Tukey's HSD test has been applied. The comparison has been done for one parameter, and that is BOD.

$$RR(\%) = [(Ci - Ce) / Ci] \cdot 100 \quad (1)$$

The relative numbers, percentages, have been taken into consideration for the mentioned parameter (Equation 1). The *RR* is removal rate and *Ci* and *Ce* are the inflow and outflow concentration in mg/L (Chang et al., 2007).

Also, the *F* test is given by ANOVA analysis. It exhibits the ratio of variance between groups to variance within the groups. If this test is greater, then it shows that there is more variability among the groups than inside the groups (Pallant, 2007). However, it does not show which of the groups differ. Post-hoc comparison is used to explore the differences between each of the groups. In this study, the Tukey's HSD test is used (Pallant, 2007). Also, effect size has been calculated. Effect size expresses the degree to which independent and dependent variables are related (Borenstein et al., 2009; Tabachnick & Fidell, 2007). There are different types of effect size, but for this research, Eta squared effect size has been calculated which can be small, medium, or large (Pallant, 2007).

$$\eta^2 = SSeffect / SStotal \tag{2}$$

where η^2 is Eta squared, *SSeffect* is Sum of squares between groups, and *SStotal* is the total sum of squares (Borenstein et al., 2009; Pallant, 2007).

3. Results

According to the first hypothesis, CWs were compared for BOD removal efficiency. BOD removal efficiency was compared for the SF, SSF, and HYB CWs. Results are presented by box plots (Figure 1 and 2). The horizontal line in each box plot is the median value or the middle of the dataset. It represents that 50% of the data have greater efficiency than this value. Median value has been applied rather than average value because it is immune to high values and has the favor of being a more robust variable (Nicolau et al., 1989). The box presents 50% of the data and the top of the box indicates 75th percentile of the data, where the bottom of the box expresses the 25th percentile of the data. The vertical lines represent the 90th and 10th percentile of the data. Points outside this interval represent possible outliers. The width of the boxes is proportional to the number of observations per group.

3.1. BOD removal efficiency

As it was expected, all the systems operate well in case of BOD removal efficiency. This is shown in Figure 2. In case of BOD in all the systems, the efficiency of the systems is greater than 67%. HYB systems are the most efficient ones. The second place goes to SSF CWs, while SF systems have the lowest efficiency (Table 2).

Table 2. Summary results of BOD efficiency for three systems

Type	Mean (%)	Standard deviation	N	Max (%)	Min (%)
HYB	81.76	21,83	33	100	18
SF	67.23	22,76	75	99.0	19
SSF	74.92	19,30	226	100	8

Note. SF − surface flow; SSF – subsurface, and HYB − hybrid systems; N = number of data.

The ANOVA analysis conducted for BOD reveals a significant disparity among the systems, as reflected in the *p*-value, leading to the rejection of the H_0 hypothesis (Table 3). This statistical finding underscores the presence of notable variations between the examined systems in terms of their impact on BOD pollution. Furthermore, the significance of this result suggests that different systems may have distinct levels of effectiveness in mitigating BOD, warranting further investigation into potential factors contributing to this discrepancy.

Table 3. Summary results for ANOVA analysis for BOD efficiency

	Degree of freedom	Sum of square	Mean of square	*F* value	Pr (>*F*)
Type	2	5610	2805.2	6.756	0.00133 **
Residuals	331	137425	415.2		

Further analysis through Post-hoc comparisons employing the Tukey HSD test indicates a significant discrepancy in the average values between the HYB and the SF CWs (Figure 1). This finding highlights distinct performance levels between the two types of CWs, suggesting that the HYB design may yield notably different outcomes compared to the SF configuration. The observed disparity underscores the importance of considering various wetland construction approaches when assessing their efficacy in pollutant removal. Additionally, these results prompt potential inquiries into the specific mechanisms or design features driving the differences in performance between HYB and SF CWs.

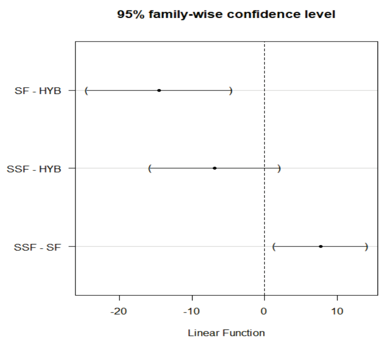

Figure 1. Difference in means level between the systems for BOD removal efficiency.
Note. SF – surface flow; SSF – subsurface; HYB – hybrid systems.

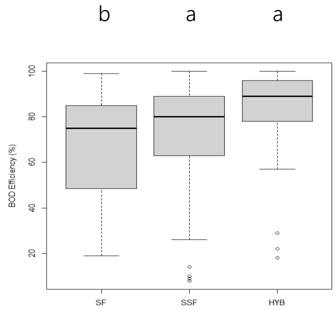

Figure 2. Comparison between three systems for BOD removal efficiency (%).
Note. SF – surface flow; SSF – subsurface; HYB – hybrid systems.

Also, Post-host comparisons indicate that mean scores for the SSF CWs are significantly different from the SF CWs. The family-wise confidence level plot, constructed at a 95% threshold, indicates that comparison between SSF and hybrid HYB CWs yield statistically insignificant results. This discrepancy is further corroborated by the lettering system (b, a, a) on the plot (Figure 2), which shows significant differences between groups. This suggests a similarity in performance or efficacy between SSF and HYB CWs.

3.2. Effect size

The calculated Eta squared value of 0.039 (Table 4) for BOD removal efficiency indicates that approximately 3.9% of the variance in this dependent variable can be attributed to the independent variable, specifically the different types of CWs. This substantial effect size signifies a notable impact of the wetland types on BOD removal efficiency, suggesting that the choice of wetland design significantly influences the effectiveness of pollutant removal. This statistical insight underscores the importance of considering CW configurations when designing wastewater treatment systems. Actually, the relative magnitude of the differences between the mean values for these three types of CWs for BOD is high.

Table 4. Effect size results

Pollutants		Sum of squares	Effect size
BOD efficiency (%)	Between groups	5610	0.039
	Within groups	137425	
	Total	143035	

4. Discussion

In this research, BOD removal efficiency is within the range 67–82% (Table 2). SF CWs has the minimum mean value for removal efficiency and that is above 67%, but HYB systems have the highest mean value of almost 82%. SSF CWs with almost 75% of mean value for removal efficiency follow the maximum mean value for HYB systems. Moreover, maximum values for removal efficiency for all the three systems are almost the same (Table 2). Nevertheless, ANOVA shows that there is a statistically important difference between these three systems. According to the literature, removal of organics for all the types of CWs is very high (Vymazal, 2005). Removal of organic substances for CWs is typically 80–90% (Shutes, 2001; Verhoeven et al., 1999). Generally, CWs can be designed in such a way as to remove more than 90% of BOD (Kadlec et al., 2000). Therefore, the results for the CWs removal efficiency given in this research, in the case of organics, have similar values as results provided in the literature. Nevertheless, there are differences between different types of CWs, but this could be influenced by various removal processes which can have a greater or smaller role in some of these systems. The type of plant that is used in CWs could influence the BOD removal efficiency as well as the retention time of waste water within the system. BOD removal efficiency in CW was as follows: 98.19% for *Hydrilla verticillata* (waterthyme), 98.74% for *Eleocharis dulcis* (Chinese water chestnut), 98.48% for *Nelumbo* nucifera (sacred lotus), and 98.89% for a combination of *Hydrilla verticillata* (waterthyme), *Eleocharis dulcis* (Chinese water chestnut), and *Nelumbo nucifera* (sacred lotus) with time span of 12 days (Prihatini et al., 2017). At the retention time of seven days, BOD removal efficiency was 41% (Lokesh et. al., 2023). In the SF CWs, organic matter removal efficiency is affected by quiescent conditions. To enhance BOD removal efficiency, reaeration at the water surface is employed as an oxygen source for microbial BOD removal (Watson et al., 1989). In this research, SF CWs show good BOD removal efficiency. In HF CWs, both aerobic and anaerobic conditions are present. The oxygen is used by bacteria to oxidize organic matter and they are attached to substrate surface or plant roots (Watson et al., 1989).

Generally, HF and VF CWs can have high purification levels (Luederitz et al., 2001). From this research it can be concluded that SSF systems have good efficiency performance for the removal of the BOD. It is accepted that HF systems are good for BOD removal and VF systems are also good in BOD removal (Brix & Johansen 1999; Cooper, 2005). In the VF CWs in Italy, Austria, Denmark, and Slovenia, the average BOD removal efficiency ranges from 54% up to 78% (Didanovic & Vrhovsek, 2023). Vegetation in VF CWs plays a crucial and statistically significant role in the removal of BOD. The planted VF CWs achieved an average BOD removal rate of 84%, whereas the unplanted ones only achieved 36% (Abdelhakeem et al., 2016). In another research, the removal efficiency of BOD reached 88%. The design features of VF CWs promote an optimal aerobic environment conducive to enhanced decomposition of organic compounds (Singh et al., 2023). As a possible solution for better removal performances, a HYB system has been developed by Seidel at the Max Planck Institute (Vymazal, 2005). In a two-stage HYB system made of one HF and another VF CW, the strengths of both systems are utilized. The debate around which system should be placed as the first or the second is important when considering better removal processes. HF systems, in the first stage, provide good removal of solids reducing the clogging in the second stage or in the VF system. Moreover, HF in the first stage removes as much BOD as possible. Besides, the VF stage in the first place provides satisfactory BOD (Cooper, 2001). The performance of HYB system where hydraulic retention time was four days in case of BOD removal efficiency was maximum 78% and 84% with *Typha Angustifolia* (narrowleaf cattail) in the first and *Pistia Stratiotes* (water lettuce) planted in the second scenario (Haydar et al., 2020). Nevertheless, there are still some uncertainties regarding how some factors influence the removal process. Regarding the design and functioning of CWs, there are several main points often highlighted in the literature such as consideration of local climate conditions and seasonal changes, determining the appropriate shape, ratios between the area of CW and the catchment, as well as the length-to-width ratios, establishing the flow direction within CW, incorporating appropriate hydraulic structures for efficient operation, designing the configuration of inlet and outlet points for optimal performance, ensuring successful establishment of vegetation within the CW and implementing regular harvesting of vegetation within CW (Nan et. al., 2023).

5. Conclusion

Following wastewater treatment in CWs for BOD removal efficiency can reach levels as high as 82%, as shown in this research, indicating the substantial effectiveness of CW systems in mitigating organic pollutants from wastewater. These high removal rates emphasize the ability of CWs to substantially decrease BOD released into receiving water bodies, thus enhancing water quality. Additionally, it is shown that statistical comparison between different types of CWs, in the case of SSF and HYB systems fails to reach statistical significance, as indicated by the identical letters assigned to these groups (a, a). This suggests a similarity in performance or efficacy between SSF and HYB CWs, warranting closer examination to discern potential factors contributing to this observation. On the other side, the statistically significant difference between SF and SSF or between SF and HYB systems underscore the nuanced dynamics at play in comparing different types of CWs and highlight the need for comprehensive statistical analyses to elucidate meaningful distinctions. The research is constrained by the grouping of data from both VF and HF SSF under the category of SSF CWs, without differentiation. This amalgamation occurred due to insufficient data available for VF CWs and a lack of information specifying the type of SSF CW in the publications. Furthermore, the inability to separate and analyse VF and HF SSF CWs individually may impact the overall findings of the study. Additionally, this research shows that CWs are good systems for BOD removal efficiency. Having in mind that they are imitations of natural processes and where natural processes are manmade and controlled, their application for BOD removal efficiency is quite satisfactory. Moreover, these systems are used worldwide which justifies the fact that they can be used in different climate conditions. Also, this shows that there is great attention on CWs proven by their application on almost every continent. Nevertheless, there is a difference between different types of

CWs in the case of BOD removal efficiency. For BOD removal efficiency, SSF and HYB systems have been shown to be more efficient in comparison with SF CWs. The mean value for HYB systems shows a better BOD removal efficiency in comparison with other systems, SF and SSF (Table 3). Therefore, the mix of VF and HF SSF CWs or SF systems should have better removal efficiency than any of these systems alone. The implementation of the HYB system which is made of various types of CWs is one point of research gap, especially in the case of their performances in order to have higher removal efficiency. Therefore, there is a need for future research related to the combinations of different types of CWs within the HYB systems. It should have better attention and research priorities in order to gain knowledge about which combination of CWs is the best one, which types of waste waters can be treated, and finally, what are the performances of different combinations. Furthermore, it is imperative to undertake investigations concerning the efficacy of CWs in purifying wastewater, encompassing various parameters related to wastewater quality, including but not limited to chemical oxygen demand, total suspended solids, total nitrogen, total phosphorus, and other pertinent factors.

Another important aspect is the type of plants that are used in constructed wetlands. The use of various plants and the number of plants in a system can have greater attention. Various types of plant species have been used in different systems. However, the question which plant might have best application for different pollutants has not yet been resolved. In this respect it should be seen whether or not the bigger number of plants or plant diversity influence the final performance of CWs. However, the long-term stability of these systems' efficiency remains uncertain. Therefore, further research with combination of plants and extended retention time is necessary to explore this aspect. One of the gaps is related to the design of CWs. Actually, the question is about which area or the size of the CW is good enough to acquire the satisfactory output after waste water treatment. The system configuration in case of the length-width ratio and its influence to final performance still requires studying in order to determine the optimal length-width ratio for satisfactory performance. Additionally, the variability in treatment outcomes related to factors such as the presence of plants, media type, and feeding method in CWs indicates the necessity for additional research to enhance the system's performance. Moreover, further investigation is needed to evaluate the impacts of certain parameters, such as flow direction and the utilization of deep zones. Therefore, there are various factors which can influence final performance, thus the prioritization regarding systems should be carefully considered.

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