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Systematic Review

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Energy and Water-Saving Strategies for Data Center Cooling in Tropical Climates: A Literature Review with a Bangkok Case Example

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Abstract: Data centers in tropical climates face distinct cooling challenges. High ambient temperature and humidity limit free-cooling opportunities, which often raises Power Usage Effectiveness (PUE) and Water Usage Effectiveness (WUE) above the levels seen in temperate regions. This paper reviews existing studies on energy- and water-saving strategies for data center cooling, with emphasis on hot-humid climates, and identifies research gaps relevant to Thailand. The reviewed strategies are zone and supply-air setpoint, chilled-water temperature, free cooling and economizers, cooling-tower water management, and system design factors such as redundancy and rack density. The literature shows that savings reported in temperate climates, including up to 68% cooling-energy savings from economizers, do not transfer to hot-humid zones, where a water-side economizer returned 0% savings and an indirect evaporative cooler 7.5%. Most studies report PUE alone, and none of the studies compared here reports a water metric next to it. A short case example, based on a preliminary EnergyPlus simulation of a 2 MW data center in Bangkok, illustrates these findings: no free-cooling hours, a 20% water saving from raising cooling-tower cycles of concentration from 3 to 6, and a combined scenario that reduced PUE from 1.39 to 1.38 and WUE from 3.02 to 2.40 L/kWh. The review concludes that operational measures alone are unlikely to meet common PUE and WUE targets in Thailand, and that evaporative cooling, equipment-level upgrades and studies that report water alongside energy deserve further attention.

Keywords: Data center cooling; Tropical climate; Power Usage Effectiveness (PUE); Water Usage Effectiveness (WUE); Free cooling

1. INTRODUCTION

The rapid growth of digital services, cloud computing and artificial intelligence has led to a substantial increase in global data center electricity demand. According to the International Energy Agency [1], data centers consumed approximately 415 TWh of electricity in 2024, accounting for about 1.5% of worldwide electricity use. Cooling systems represent a major share of this consumption. Previous studies have shown that cooling can account for 30–50% of total data center energy use, especially in less efficient facilities [2], [3].

In tropical climates, the cooling challenge becomes more critical. High ambient temperature and humidity throughout the year significantly reduce the potential of free cooling and air-side economizers [4], [5]. As a result, air-cooled data centers in tropical regions often operate with higher Power Usage Effectiveness (PUE) and Water Usage Effectiveness (WUE) values compared to those located in cooler climates.The thermoeconomic assessment of an air-cooled tropical data center demonstrated that raising the supply air temperature and applying optimized control strategies can achieve energy savings of 9.1–14.7% [6]. ASHRAE Thermal Guidelines for Data Processing Environments [7] provide recommended and allowable temperature and humidity ranges that can support higher operating temperatures and improve free-cooling opportunities. However, the actual performance of these strategies under Thailand's hot-humid climate still requires detailed evaluation.

Dynamic simulation tools such as EnergyPlus, TRNSYS and Modelica have been widely used to analyze data center cooling systems [8]–[10]. However, most published work addresses temperate climates, and studies of several strategies side by side under hot-humid conditions are

limited. Water use is also rarely reported next to energy, even though water-cooled plants in the tropics can consume large volumes of cooling-tower makeup water. Because the findings are spread across different climates, tools, system types and metrics, a structured comparison is needed to see what can be transferred to Thailand.

This paper therefore reviews the existing literature and has three objectives: (1) to summarize the main energy- and water-saving strategies for data center cooling and the metrics used to evaluate them, (2) to compare reported results for temperate and tropical climates, with emphasis on hot-humid conditions, and (3) to identify research gaps relevant to Thailand. A short case example, based on a preliminary EnergyPlus simulation of a 2 MW data center in Bangkok by the author, is included to illustrate how the reviewed findings play out in a Thai context. It is not presented as a full original study.

2. MATERIALS AND METHODS

2.1 Scope and search strategy

The review covers peer-reviewed articles, standards and technical reports on data center cooling energy and water performance, with emphasis on studies in tropical or hot-humid climates. Literature was collected from ScienceDirect, Scopus and Google Scholar using combinations of the keywords *data center cooling*, *energy efficiency*, *PUE*, *WUE*, *tropical climate*, *free cooling*, *economizer*, *EnergyPlus* and *simulation*. Reference lists of key papers were also screened to find additional relevant work.

2.2 Selection criteria

Studies were included if they (a) addressed energy or water performance of data center cooling systems, (b) reported quantitative results or a clear methodology, and (c) were published in a peer-reviewed journal or by a recognized standards or government body. Priority was given to studies in tropical or hot-humid climates and to those using dynamic simulation. Studies from temperate climates were kept as reference points, since they show how results change with climate.

2.3 Analysis framework

The selected studies were compared by climate and location, system type, strategy tested, modelling or measurement method, and reported results. Two metrics, represented by Equations (1) and (2) are used throughout, as defined in the literature [11], [12]:

$$PUE = \frac{E_{total}}{E_{IT}} \quad (1)$$

$$\mathbf{WUE} = \frac{\mathbf{V_{water}}}{\mathbf{E_{IT}}} \quad (2)$$

Where E_{total} is the total annual facility electricity (kWh), E_{IT} is the annual IT equipment electricity (kWh), and V_{water} is the annual makeup water (L). PUE is dimensionless and WUE is expressed in L/kWh.

PUE is the most common efficiency indicator, but it has known limitations: it can be improved without reducing absolute consumption, and it is sensitive to the period over which it is measured [12]. WUE is reported far less often. Both metrics are therefore considered alongside absolute energy and water savings.

The strategies are grouped into five themes: supply-air and zone setpoint, chilled-water temperature, free cooling and economizers, cooling-tower water management, and system design factors (redundancy and rack density).

2.4 Case example: Bangkok simulation

To illustrate the reviewed findings, a preliminary simulation was carried out in EnergyPlus for a representative 2 MW Tier III data center with N+1 water-cooled chilled-water plant in Bangkok (ASHRAE climate zone 0A), using a Bangkok TMYx weather file. IT equipment was modelled with the ElectricEquipment:ITE:AirCooled object so that server and fan power respond to inlet air temperature, and operating ranges followed ASHRAE guidance [7]. The baseline was then compared with a zone setpoint sweep, elevated chilled-water temperature, a water-side economizer, higher cooling-tower cycles of concentration, and a combined scenario. The simulation is used only to compare against the reviewed studies and is not intended to replace the review.
Figure 1 summarizes the procedure followed in this review.

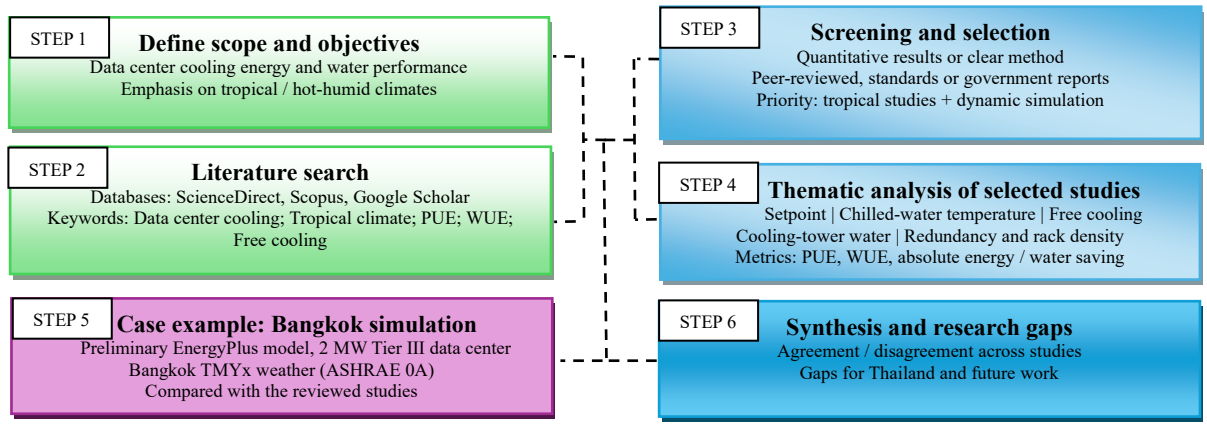


Figure 1. Research methodology and procedure of the literature review

3. RESULTS AND DISCUSSION

3.1 Literature benchmark

Table 1 summarizes the studies that are most directly comparable, grouped by climate. Only one isolates the hot-humid zone relevant to Thailand, which is a first indication of the research gap.

Table 1. Comparable cooling-strategy studies for data centers

Study	Climate / case	Strategy tested	Reported result
[5]	17 global climate zones, incl. 1A (Singapore)	Water-side economizer, indirect evaporative cooler (IEC), vs. air-cooled chiller baseline	Zone 1A: economizer 0% savings (0 operating hours); IEC 7.5% savings. Zones 4–7: IEC >33%; economizer >25–30%
[6]	Singapore testbed (tropical)	Raise supply-air temperature 20–32°C + dynamic control	9.1–14.7% annual energy savings
[8]	Salem, Oregon (temperate)	Waterside economizer	Active ~42% of the year; CRAH fans = 50.9% of cooling energy
[10]	Industry survey (global)	Critique of PUE as an instantaneous metric	Typical annual PUE 1.79–1.89; recommends time-averaged PUE/EUE over ≥1 year
[13]	Seoul (temperate)	Air-side economizer with evaporative pre-cooling	Up to 68% cooling-energy savings
[14]	Global literature review	PUE and thermal-environment benchmarking	Average reviewed PUE = 2.23; average IT share of total power = 44.8%

The table shows a clear pattern. The largest savings come from temperate locations, where outdoor air can be used directly or through an economizer for much of the year [8], [13]. In the hot-

humid zone, the same strategy returns little or nothing [5]. Results from temperate studies therefore cannot be transferred to Thailand without checking them against local weather.

3.2 Performance metrics: PUE and WUE

Most reviewed studies evaluate performance with PUE alone. Yuventi and Mehdizadeh [10]argue that PUE, particularly when taken at a single point in time, can misrepresent real consumption and should be averaged over at least a year. The averages reported in the literature vary widely, from 1.79–1.89 in industry surveys [10] to 2.23 across the studies reviewed by Ghifari et al. [14], so a PUE value is only meaningful when the climate, load and system type are stated.

Of the studies in Table 1, none reports a water metric alongside PUE. This matters in the tropics, where water-cooled plants rely on evaporative cooling towers. Radiative free cooling has been proposed as an option that saves both energy and water [4], but water-side measures are still much less studied than energy-side ones. A fair comparison of strategies in hot-humid climates should therefore track WUE together with PUE and absolute savings.

3.3 Supply-air and zone setpoint

Raising the supply-air or zone setpoint is among the most frequently recommended measures, since ASHRAE guidelines allow operation at higher inlet temperatures [7]. In a tropical air-cooled facility, Zhou et al. [6] reported savings of 9.1–14.7% when supply-air temperature was raised and combined with dynamic control. The benefit arises mainly because chillers operate more efficiently at warmer setpoints, while server power is assumed not to change.

This assumption is important. Server fans and processors draw more power as inlet temperature rises, so a higher setpoint can shift energy from the cooling system to the IT equipment. Studies that treat IT power as fixed will therefore show larger savings than studies that model IT power as temperature-dependent. The reviewed literature does not always state which approach is used, which makes direct comparison difficult. Related work on chilled-water supply temperature points the same way: a warmer chilled-water setpoint improves chiller efficiency, but only up to the point where the cooling coils can still hold the required zone temperature.

3.4 Free cooling and economizers

Free cooling is the strategy with the clearest climate dependence. In temperate locations, economizers have large potential: Cho et al. [14] report up to 68% cooling-energy savings in Seoul, and Fu et al. [8] found a water-side economizer active for about 42% of the year in Oregon. In contrast, Agrawal et al. [5] found 0% economizer savings and zero operating hours in climate zone 1A, while an indirect evaporative cooler still achieved 7.5%. This agrees with the general observation that high ambient temperature and humidity limit free cooling in the tropics [4], [5].

Two conclusions follow. First, a water-side economizer should not be assumed to be a viable saving measure in Thailand. Second, evaporative and other hybrid approaches deserve more attention for hot-humid climates, since they still show a positive saving where economizers do not.

3.5 Cooling-tower water management

Water use in chilled-water plants is dominated by cooling-tower makeup water, which depends on evaporation and blowdown. Raising the cycles of concentration reduces blowdown and therefore makeup water, without changing the thermal performance of the plant. Because this effect appears only in a water metric, it is invisible in studies that report PUE alone [10]. Few of the reviewed studies quantify this lever, which is a gap given that water availability is a growing concern for data centers.

3.6 Redundancy and rack density

Redundancy (N, N+1, 2N) and rack density are design choices that affect energy use mainly

through part-load operation, fan power and airflow. Tier-based redundancy is a reliability requirement and is not usually treated as an energy-saving option. The reviewed studies give little quantitative guidance on how these factors behave in tropical climates, and resolving rack-level airflow effects requires models that are more detailed than single-zone representations [8], [9]. This is another area where the literature is thin. [15]

3.7 Case example: Bangkok simulation

To illustrate the reviewed findings in a Thai context, the preliminary EnergyPlus simulation described in Section 2.4 was compared with the studies above. The baseline gave a PUE of 1.39 and a WUE of 3.02 L/kWh. Table 2 lists the main results and how each relates to the reviewed literature.

Table 2. Energy and water results of the preliminary EnergyPlus simulation of a 2 MW Tier III data center in Bangkok (baseline PUE 1.39, WUE 3.02 L/kWh) for five cooling strategies, compared with findings from the reviewed studies.

Strategy (Bangkok case)	Result in case example	Relation to the literature
Water-side economizer	0 operating hours per year	Agrees with Agrawal et al. [5] (0% savings in zone 1A)
Cycles of concentration 3 → 6	−20.0% water, 0.0% energy change	Supports tracking WUE alongside PUE [10]
Zone setpoint 22–27 °C	Energy −14.3% at 22 °C to +21.9% at 27 °C, PUE almost flat	Opposite direction to Zhou et al. [6]
Chilled-water supply 18–20 °C	Energy −6.0% at 18 °C, rising above this	Consistent with the limit on warmer chilled water in Section 3.3
Combined scenario (22 °C setpoint, cycles of concentration 6, chiller dispatch)	PUE 1.38, WUE 2.40 L/kWh, energy −15.2%, water −32.1%	Short of common targets (PUE 1.3, about 2 L/kWh or lower)

The setpoint result differs from Zhou et al. [6] because of how IT load is modelled. The case example uses a temperature-sensitive IT load, so server and fan power rise as the setpoint rises and outweigh the chiller saving, whereas a model with fixed IT power shows a saving. Neither is wrong; they represent different IT hardware assumptions. The case example is indicative only: it uses a single-zone model, a single location and a default-based chiller performance, so its numbers should be read as an illustration of the trends in the literature, not as design values.

Figure **2** shows the main trends of the case example. PUE and WUE change truly little across the setpoint range (panel a), yet absolute energy and water use change by tens of percent (panel b). This is the reason ratio metrics should be read together with absolute savings. Chilled-water temperature gives a benefit only up to 18–20 °C (panel c), and the combined scenario lowers WUE much more than PUE (panel d).

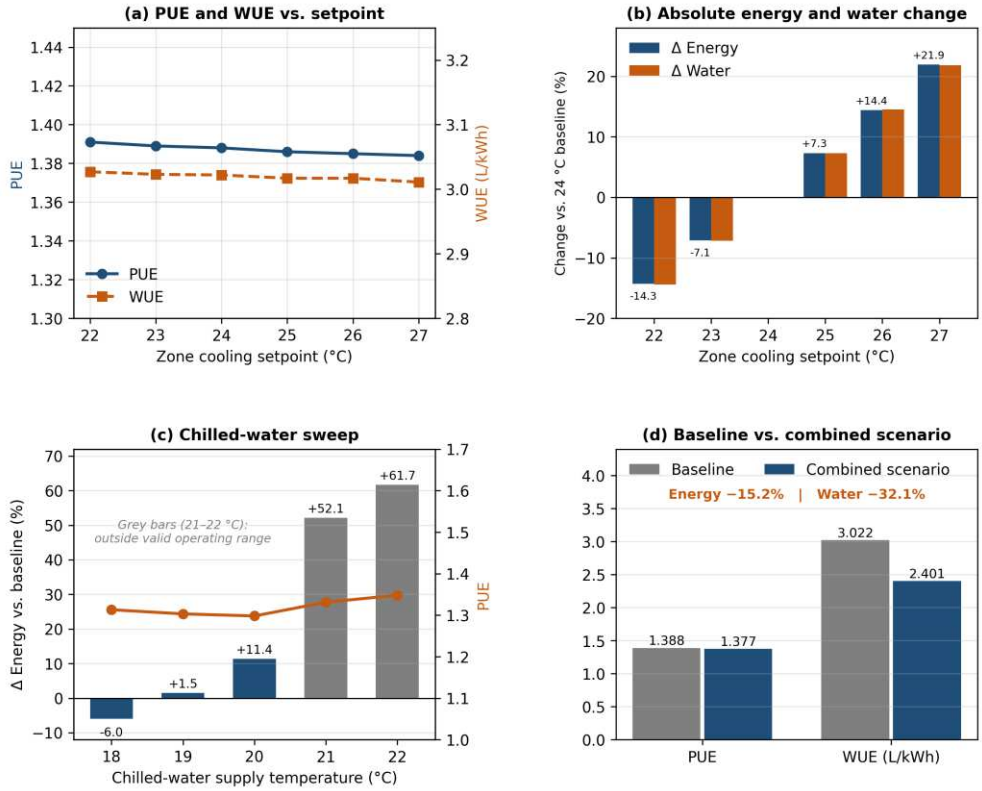


Figure 2. Case example results for the Bangkok data center:(a) PUE and WUE vs. zone setpoint, (b) energy and water change vs. setpoint, (c) chilled-water supply temperature sweep, (d) baseline vs. combined scenario.

3.8 Discussion

The absence of free-cooling potential in Bangkok matches the zone 1A result of Agrawal et al. [5], even though the two studies use different tools (EnergyPlus and TRNSYS), different loads and different weather years. Agreement across independent studies strengthens the conclusion that water-side free cooling is not viable in hot-humid climates.

The setpoint result runs opposite to Zhou et al. [6]. The difference comes from the modelling of IT power rather than from an error in either study, and it shows that the benefit of a higher setpoint depends on the IT hardware. Facilities with less temperature-sensitive servers would be expected to behave more like the result in [6].

Figure 2 shows that PUE and WUE barely changed across the setpoint range, even though absolute energy and water use changed by tens of percent. This happens because IT power rises together with cooling energy, so the ratio stays almost flat while the facility consumes much more. It supports the argument of Yuventi and Mehdizadeh [10] that PUE alone can misrepresent real consumption. A strategy should therefore be judged on absolute energy and water savings as well as on PUE and WUE, which most of the reviewed studies do not do.

This review has three limitations. First, only a small number of directly comparable studies exist for hot-humid climates, so conclusions about the tropics rest on few sources. Second, the studies differ in tools, loads, weather files and metric definitions, so numerical comparisons are indicative rather than exact. Third, the review is not a full systematic review with screening statistics. The case example has its own limits: it is a single-zone model for one location, it uses default-based chiller performance, and it has not been validated against measured data from a Thai facility. Its numbers are therefore an illustration of the reviewed trends and not design values.

4. CONCLUSION

This paper reviewed existing studies on energy- and water-saving strategies for data center cooling and compared results from temperate and tropical climates. The main conclusion is that the benefit of a cooling strategy depends strongly on climate, so results from temperate locations cannot be applied directly to Thailand.

Three findings stand out. First, free cooling is the strategy with the clearest climate dependence. Economizers reached large savings in temperate studies , but returned 0% savings in a hot-humid zone, where an indirect evaporative cooler still gave 7.5% . Second, the benefit of a higher setpoint depends on how IT power is modelled: studies that hold IT power fixed report savings, while a temperature-sensitive IT load can reverse the result. Third, PUE is the dominant metric, but it can hide changes in absolute consumption, and water measures such as higher cooling-tower cycles of concentration appear only when WUE is reported.

The Bangkok case example agreed with this picture. It found no free-cooling hours, a 20% water saving from raising cycles of concentration with no energy penalty, and a combined scenario that reduced energy by 15.2% and water by 32.1% (PUE 1.39 to 1.38, WUE 3.02 to 2.40 L/kWh), which is still short of common targets. These results come from a single-zone preliminary model and illustrate the reviewed trends. They are not design values.

5. REFERENCES

[1] International Energy Agency (IEA), “Energy Statistics Data Browser and Greenhouse Gas Emissions from Energy,” *International Energy Agency*, 2025. https://www.iea.org/data-and-statistics.

[2] S. Cai and Z. Gou, “Towards energy-efficient data centers : A comprehensive review of passive and active cooling strategies,” *Energy Built Environ.*, vol. 7, no. August 2024, pp. 206–226, 2026, doi: 10.1016/j.enbenv.2024.08.009.

[3] L. Gibbons, T. Persoons, and S. Alimohammadi, “Techno-Economic and Sustainability Analysis of Potential Cooling Methods in Irish Data Centres,” *J. Electron. Cool. Therm. Control*, pp. 35–54, 2021, doi: 10.4236/jectc.2021.103003.

[4] A. Aili, W. Long, Z. Cao, and Y. Wen, “Radiative free cooling for energy and water saving in data centers,” *Appl. Energy*, vol. 359, no. December 2023, p. 122672, 2024, doi: 10.1016/j.apenergy.2024.122672.

[5] A. Agrawal, M. Khichar, and S. Jain, “Transient simulation of wet cooling strategies for a data center in worldwide climate zones,” *Energy Build.*, vol. 127, pp. 352–359, 2016, doi: 10.1016/j.enbuild.2016.06.011.

[6] J. Zhou, B. Burak, D. Van Le, R. Tan, and F. Duan, “Thermoeconomic assessment of the air-cooled tropical data center through energy-saving strategies,” *Energy Built Environ. J.*, vol. 7, no. February 2024, pp. 115–127, 2026, doi: doi.org/10.1016/j.enbenv.2024.07.006.

[7] ASHRAE TC 9.9, “Data Center Power Equipment Thermal Guidelines and Best Practices,” 2016. [Online]. Available: https://www.ashrae.org/file library/technical resources/bookstore/ashrae_tc0909_power_white_paper_22_june_2016_revised.pdf.

[8] Y. Fu, W. Zuo, M. Wetter, J. W. Vangilder, X. Han, and D. Plamondon, “Equation-base d object-oriente d modeling and simulation for data center cooling : A case study,” *Energy Build.*, vol. 186, pp. 108–125, 2019, doi: 10.1016/j.enbuild.2019.01.018.

[9] Y. Fu, W. Zuo, M. Wetter, J. W. Vangilder, and P. Yang, “Energy & Buildings Equation-base d object-oriente d modeling and simulation of data center cooling systems,” *Energy Build.*, vol. 198, pp. 503–519, 2019, doi: 10.1016/j.enbuild.2019.06.037.

[10] J. Yuventi and R. Mehdizadeh, “A critical analysis of Power Usage Effectiveness and its use in communicating data center energy consumption,” *Energy Build.*, vol. 64, pp. 90–94, 2013, doi: 10.1016/j.enbuild.2013.04.015.

[11] J. Ni and X. Bai, “A review of air conditioning energy performance in data centers,” *Renew. Sustain. Energy Rev.*, vol. 67, pp. 625–640, 2017, doi: 10.1016/j.rser.2016.09.050.

[12] V. Ganesh, H. Li, M. Maloney, and W. Zuo, “SoftwareX DCOPTEST : A novel unified virtual testbed for data center cooling systems,” *SoftwareX*, vol. 36, no. June, p. 103073, 2026, doi: 10.1016/j.softx.2026.103073.

[13] J. Cho, J. Yang, C. Lee, and J. Lee, “Development of an energy evaluation and design tool for dedicated cooling systems of data centers : Sensing data center cooling energy efficiency,” *Energy Build.*, vol. 96, pp. 357–372, 2015, doi: 10.1016/j.enbuild.2015.03.040.

[14] Z. Ghifari, M. Setyo, H. B. Rijal, N. Aqilah, and N. Abdullah, “Energy Efficiency Measurement Method and Thermal Environment in Data Centers — A Literature Review,” *Energies*, vol. 3689, no. July 2025, pp. 1–17, 2025, doi: .org/10.3390/en18143689.

[15] H. Cheung and S. Wang, “Reliability and availability assessment and enhancement of water-cooled multi-chiller cooling systems for data centers,” *Reliab. Eng. Syst. Saf.*, vol. 2, pp. 1–39, 2019, doi: 10.1016/j.ress.2019.106573.