

S1: Summary of guidelines on ventilation, thermal comfort

Table S1 Summary of guidelines specified in Building Bulletin 101 (BB101, 2018 version) [31]

Parameter	Focus area	Description
Pollutant concentration	CO2 NO2 Formaldehyde TVOCs	Max 1,500 ppm (daily average); 5,000 ppm not to be exceeded $\leq 40 \mu\text{g}/\text{m}^3$ annual mean (outdoor) $\leq 100 \mu\text{g}/\text{m}^3$ (30-min, avg) $\leq 300 \mu\text{g}/\text{m}^3$ (8-hr, avg) Use low-emission materials and manage sources like 3D printers
Ventilation rates	General teaching areas Specialist areas such as labs Purge ventilation CO2 monitoring	≥ 5 l/s per person ≥ 8 l/s per person ≥ 4 air changes/hour recommended in all teaching spaces
Avoidance of overheating	Winter indoor temp: Summer max temp Overheating	$\geq 18^\circ\text{C}$: Adaptive comfort model used (based on external temp): Max 60 hours/year $> 28^\circ\text{C}$ Use passive cooling (e.g. night ventilation, thermal mass) Avoid cold draughts and ensure comfort for pupils with disabilities

Table S2: Summary of international and government guidelines and regulations for specific pollutants, temperature, and relative humidity, outlined in the International Society of Indoor Air Quality and Climate (ISIAQ) database [29, 30]

Parameter	Value	Averaging Time	Countries	Category	Year Published	Environment
Temperature (operative)	Winter 18°C - 25°C , summer ATG = 0,33 * ambient T + 16,4 +/-4 or in case of cooling $<27^\circ\text{C}$		Netherlands	Non-governmental Guideline	2021	School; Class C
Temperature (operative)	Winter 19°C - 24°C , summer ATG = 0,33 * ambient T + 16,4 +/-3 or in case of cooling $<26^\circ\text{C}$		Netherlands	Non-governmental Guideline	2021	School; Class B
Temperature (operative)	Winter 20°C - 23°C , summer ATG = 0,33 * ambient T + 16,4 +/-2 or in case of cooling $<25,5^\circ\text{C}$		Netherlands	Non-governmental Guideline	2021	School; Class A
Temperature	$\geq 19^\circ\text{C}$		Estonia	Government Regulation	2013	School

Temperature	18-23°C		United Kingdom	Government Guideline		School
Temperature	18-28°C	Ceiling limit	South Korea	Government Regulation	2019	School
Temperature	17-28°C		Japan	Government Regulation		School
RH	30-80%	Ceiling limit	South Korea	Government Regulation	2019	School
RH	30-80%		Japan	Government Regulation		School
RH	40-75%		United Kingdom	Government Guideline		School
RH	40-60%		Estonia	Government Regulation	2013	School
CO ₂	1200 ppm		Netherlands	Non-governmental Guideline	2021	School
CO ₂	950 ppm		Netherlands	Non-governmental Guideline	2021	School
CO ₂	800 ppm		Netherlands	Non-governmental Guideline	2021	School
CO ₂	1000 ppm		Estonia	Government Regulation	2013	School
CO ₂	1500 ppm	Ceiling limit	South Korea	Government Regulation	2019	School
CO ₂	1,000-1,500 ppm		United Kingdom	Government Guideline	2018	School
CO ₂	1,000 ppm		New Zealand	Government Guideline		School
CO ₂	1500 ppm		Japan	Government Regulation		School
CO ₂	1200 ppm		Denmark	Government Guideline		School
CO ₂	a) average 1500 ppm (full school day); b) max 5000 ppm (throughout the day)		Lithuania	Government Regulation	2011	School
PM ₁₀	75 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
PM ₁₀	150 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
PM _{2.5}	35 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
NO ₂	40 µg/m ³	1 hour	United Kingdom	Government Guideline	2018	School
NO ₂	200 µg/m ³	1 hour	United Kingdom	Government Guideline	2018	School

NO ₂	0.05 ppm	Ceiling limit	South Korea	Government Regulation	2019	All buildings *
CO	7 mg/m ³	24 hour	WHO	International Guideline	2010	All buildings
CO	7 mg/m ³	24 hour	United Kingdom	Government Guideline	2018	School
CO	10 mg/m ³	8 hour	WHO	International Guideline	2010	All buildings
CO	10 mg/m ³	8 hour	United Kingdom	Government Guideline	2018	School
CO	35 mg/m ³	1 hour	WHO	International Guideline	2010	All buildings
CO	30 mg/m ³	1 hour	United Kingdom	Government Guideline	2018	School
CO	60 mg/m ³	30 min	United Kingdom	Government Guideline	2018	School
CO	100 mg/m ³	15 minutes	United Kingdom	Government Guideline	2018	School
Radon	200 Bq/m ³	1 year	Estonia	Government Regulation	2013	School
Radon	No safe level; reference level = 100 Bq/m ³ , no more than 300 Bq/m ³		United Kingdom	Government Guideline	2018	School
Radon	148 Bq/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
Total Volatile Organic Compounds (TVOCs)	400 µg/m ³	Ceiling limit	South Korea	Government Guideline	2019	School
Formaldehyde	0.1 mg/m ³	30 min	WHO	International Guideline	2010	All buildings
Formaldehyde	80 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
Formaldehyde	100 µg/m ³	30 min	United Kingdom	Government Guideline	2018	School
Benzene	No safe level of exposure can be recommended		WHO	International Guideline	2010	All buildings
Benzene	No safe level		United Kingdom	Government Guideline	2018	School
Benzene	30 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
Toluene	1000 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
Ethylbenzene	360 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
Xylene	700 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School

Styrene	300 µg/m ³	Ceiling limit	South Korea	Government Regulation	2019	School
Naphthalene	0.01 mg/m ³	1 year	WHO	International Guideline	2010	All buildings
Naphthalene	10 µg/m ³	1 year	United Kingdom	Government Guideline	2018	School
Tetrachloroethylene	0.25 mg/m ³	1 year	WHO	International Guideline	2010	All buildings
Tetrachloroethene (tetrachloroethylene)	250 µg/m ³	1 year	United Kingdom	Government Guideline	2018	School
Trichloroethylene	Unit risk estimate of 4.3×10^7 per µg/m ³		WHO	International Guideline	2010	All buildings
Trichloroethylene	No safe level		United Kingdom	Government Guideline	2018	School
PAHs	No threshold can be determined		WHO	International Guideline	2010	All buildings
PAHs	No safe level		United Kingdom	Government Guideline	2018	School
Total airborne bacteria	800 CFU/m ³	Ceiling limit	South Korea	Government Regulation	2019	School

* Regulation: school classrooms neighbouring streets, classrooms with individual standalone heating devices; Guideline: daycare centre, and indoor playroom for children.

RH = Relative Humidity, CO₂ = carbon dioxide, CO = carbon monoxide, NO₂ = nitrogen dioxide, PM_{2.5} = particulate matter (<2.5 nm), PM₁₀ = particulate matter (<10 nm)

S2: Summary of existing literature reviews on adjacent topics

Table S3: Summary of previous reviews of the impact of IAQ in educational buildings

Article	Focus area	# of records	Limitations
Makaremi et al., 2024	- The relationship between higher education environments (e.g., classroom spaces) and students' dynamic wellbeing. - Employs a more holistic, community approach than previously to wellbeing.	56 (IEQ), 31 (classroom interior space)	- Does not methodologically assess quality of each study included. - Minor focus on IAQ. - Does not focus on health outcomes. - No cost-benefit analysis - Focus on adults
Roche et al., 2024	Impact of TRAP, traffic noise, heat, green space on child and adolescent physical and cognitive development.	95	- Does not focus on indoor settings, only on environmental factors around schools. - Only evaluated literature between 2017 and 2023

Al-Qutub et al., 2024	- Focus on autistic children. - Framework that explains interaction between classroom IEQ, autistic sensory processing and behaviours.	11	Systematic review found that most literature relevant to autistic people focuses on acoustic aspects of IEQ; very little to none about lighting, thermal comfort or IAQ.
Murphy et al., 2023	- Impact of IAQ (including mould) exposure in both residential and school environments. - Focus on respiratory health throughout different stages of childhood.	Not mentioned	- Strong focus on residential environments alongside schools. - Does not cover quantifiable impacts (i.e. absenteeism, academic performance, economic benefit/cost)
Fernandes et al., 2023	- Impact of school interventions on indoor and outdoor stressors related to the built and natural environment on children's exposure and health. - Ventilation interventions: green time; active travel. - Primary age (5 – 12 years)	39	- Focus on interventions in outdoor environment - Studies reviewed within were mostly rated as having a weak study design. - Aside from academic performance, does not cover absenteeism, economic benefit/cost.
Anake et al., 2023	Day care focussed: indoor pollutant levels monitored, compared to available regulations for IAQ and health, evaluate the sources and health risk effects and strategies for enhancing IAQ in DCCs.	37	- Focus only on DCCs - Does not cover quantifiable impacts (i.e. absenteeism, academic performance, economic benefit/cost)
Toyinbo 2023	IEQ parameters (ventilation, thermal comfort, moisture and mould, and cleanliness in schools), health and academic performance.	160	- Emphasis on direct impact of ventilation on performance (rather than mediated through pollution impacts on health outcomes that may influence performance). - Does not provide a cost-benefit analysis of improved IEQ.
Sadrizadeh et al., 2022	- Comprehensive review on IAQ, health and academic outcomes. - Primary focus on ventilation, thermal comfort, productivity, and exposure risk. - Considers socio-economic consequences of health and performance effects on children in classrooms.	304	- Although the subject matter is similar, there is a narrow scope on schools (and children) only. Does not consider kindergartens or higher education. - No cost-benefit analysis of interventions (though buildings' energy use is discussed).
Gartland et al., 2022	- Impacts of traffic-related air pollution (TRAP) on executive functioning in primary school-aged children. - Specifically links TRAP-related biological mechanisms (i.e., inflammation and oxidative stress) with health and cognition impacts.	13	- Focus only on primary schools, and both indoor and outdoor pollution studies. - Small study pool. 2 categories of academic outcome are outlined (attainment through standardised test scores or GPA; and controlled psychological tests), but studies that focused on indoor pollution employed psychological tests only.

			Potential bias of several papers evaluating outcomes (e.g., inattention) from the same cohort
Jia et al., 2021	- Reviews the interaction between thermal comfort, IAQ and ventilation energy consumption for educational buildings. - Control strategies for providing a comfortable indoor thermal environment and acceptable IAQ are reviewed. Strong focus on ventilation.	Not mentioned	- Does not evaluate health outcomes in relation to ventilation or IAQ. - Unclear whether this comprehensive review followed PRISMA guidelines
Osborne et al., 2021	- Focus on air quality in outdoor school environments (playgrounds, drop-off zones etc) and evaluating where children are exposed to pollution peaks. - Proposes recommendations surrounding clean air zones, greening and location of school sites.	100	- Search criteria included studies only within last decade, English language. - No focus on indoor settings. - Did not review impacts of air pollution on children's health.
Vakalis et al., 2021	Associations between LEED-specified building factors and performance outcomes (cognitive skills, standardized test scores and rates of absenteeism) in schools.	43	- Non-cognitive student health symptoms omitted. - Only relevant for LEED schools
Dovjak et al., 2020	- Health outcomes from inadequate ventilation in kindergartens - Defines key issues with requirements for minimum ventilation rates and play areas per pupil.	Not mentioned	- No performance outcomes explored. - Literature review was to inform on health effects on inadequate ventilation for health modelling only
Fisk et al., 2019	- Meta analysis of statistical studies linking different health effects to presence of damp and mould. - Cough and wheeze have highest odds ratios, less for other symptoms (asthma, nasal, dermal symptoms)	11	- Damp and mould only - Does not comment on effects on absenteeism or performance - Small number of studies (focus was on cohorts bigger than 250 students).
Fisk, 2017	- Link between ventilation rate, student performance, absenteeism and respiratory health, with a component of capital and energy use costs and economic benefit - Daycare centres through to high school	28	- Does not discuss health effects of specific pollutants, only uses CO2 and ventilation rate as a proxy for IAQ. - Reliance on cross-sectional studies, which may provide associations but not causation. - Possible positive publication bias.

Bluyssen 2017	Includes acoustic and lighting quality within wider definition of IEQ in schools	Not mentioned	No discussion of effectiveness of interventions
Salthammer 2016	- Focus on effects of warming climate on thermal environment and sources of air pollutants - Discusses health impacts and interventions	Not mentioned	Does not discuss quantifiable impacts on absenteeism and academic performance beyond health impacts.
Wargocki et al., 2013	- Intervention study analysing effects of improving classroom IAQ through air cleaners on performance - IAQ based on CO₂, ventilation rates	N/A	- Single study rather than a review - Does not discuss health, absenteeism issues
Annesi-Maesano et al., 2013	Literature review covering papers from 1992 to 2012 on health effects, caused by a wide range of individual pollutants in school buildings	141	- Does not discuss effectiveness of interventions - Does not discuss mix of pollutants, but of each in isolation.
Mendell & Heath, 2005.	- Key early review. Summary of direct associations between indoor pollution, thermal conditions and performance or attendance. - Focus on high schools, but considers potential adverse effects in a broader range of indoor environments (including non-education). - Outlines evidence for direct associations between aspects of IEQ and performance (e.g., high NO₂ and reduced school attendance; low ventilation with performance) and indirect associations (e.g., damp in homes exacerbating respiratory infections, subsequently related to reduced attendance and performance). - Critical assessment (with limitations) of all studies included.	30	- Does not focus on health outcomes. - Acknowledges a potential publication bias towards positive findings of existing studies. - Review of 2 decades ago, and lots of new research has emerged since then.

Table S4 Comparison of the scope of previous reviews of the impact of IAQ in educational buildings

Article	Sole focus on educational buildings	Sole focus on students	Sole focus on IAQ, thermal comfort	Links to health impacts	Quantifies impacts on absenteeism	Quantifies impacts on academic	Quantifies economic costs of impact	Evaluation of interventions
Makaremi et al., 2024	✓	✓						
Roche et al., 2024		✓		✓		✓		
Al-Qutub et al., 2024	✓					✓		✓
Murphy et al., 2023		✓	✓	✓				
Fernandes et al., 2023		✓				✓		✓
Anake et al., 2023	✓	✓	✓	✓				✓
Toyinbo 2023	✓	✓	✓	✓	✓	✓		
Sadrizadeh et al., 2022	✓	✓	✓	✓	✓	✓		
Gartland et al., 2022		✓	✓			✓		
Lin-Rui et al., 2021	✓	✓	✓					✓
Osborne et al., 2021		✓		✓				✓
Vakalis et al., 2021	✓	✓				✓		✓
Dovjak et al., 2020	✓	✓	✓	✓				
Fisk et al., 2019	✓	✓		✓				
Fisk, 2017	✓	✓	✓		✓	✓	✓	✓
Bluyssen 2017	✓	✓	✓	✓	✓	✓		
Salthammer 2016	✓	✓	✓	✓				✓
Wargocki et al., 2013	✓	✓	✓			✓		✓
Annesi-Maesano et al., 2013	✓	✓	✓	✓	✓	✓		
Mendell & Heath, 2005.	✓	✓	✓	✓	✓	✓		
Current study	✓	✓	✓	✓	✓	✓	✓	✓

S3: Search strings used

The following string is the full search strategy used for the OVID Medline database, similar to those used for OVID Embase and Scopus databases:

Ovid MEDLINE(R) ALL <1946 to August 15, 2024>

<https://ovidsp.ovid.com/ovidweb.cgi?T=JS&NEWS=N&PAGE=main&SHAREDSEARCHID=3eHWK8l5LK7UwCVnH8dvGBHEWDcOguS4t2HWgZyl1kjVNvdjEKMg6F5lGZl0iW2C>

- 1 exp *SARS-CoV-2/ 35238
- 2 exp *COVID-19/ 223722
- 3 (corona* adj1 (virus* or viral*)).ti,kf,kw. or (corona* adj1 (virus* or viral*)).ab. /freq=3 3845
- 4 (CoV not (Coefficient* or "co-efficien*" or covalent* or Covington* or covariant* or covarianc* or "cut-off value*" or "cutoff value*" or "cut-off volume*" or "cutoff volume*" or

"combined optimization value*" or "central vessel trunk*" or CoVR or CoVS)).tw,kw,kf.
144798

5 (coronavirus* or COVID* or 2019nCoV* or 19nCoV* or "2019 novel*" or Ncov* or "n-cov"
or "SARS-CoV-2*" or "SARSCoV-2*" or SARSCoV2* or "SARS-CoV2*" or "severe acute respiratory
syndrome*" or COVID*2).ti,kw,kf. or (coronavirus* or COVID* or 2019nCoV* or 19nCoV* or
"2019 novel*" or Ncov* or "n-cov" or "SARS-CoV-2*" or "SARSCoV-2*" or SARSCoV2* or "SARS-
CoV2*" or "severe acute respiratory syndrome*" or COVID*2).ab. /freq=3 398030

6 exp "Quality of Life"/ or Population Health/ or Health Status/ or exp *Health/ or Health
Status Disparities/ or exp "cost of illness"/ or exp life expectancy/ or disability-adjusted life
years/ or healthy life expectancy/ or life tables/ or quality-adjusted life years/ 671579

7 ("health impact*" or "health effect*" or "quality of life" or "life expectancy" or QALY or
DALY or "adust* life year" or "health impact assessment" or HIA or "burden of disease" or "cost
of illness").kf,kw,tw. 533434

8 exp *Respiratory Tract Diseases/ or exp *Respiratory Tract Infections/ or exp *Lung
Diseases, Obstructive/ 1558352

9 (asthma or ((respiratory or lung or pulmonary) adj2 (infection or disease)) or
COPD).kf,kw,tw. 381829

10 *Community-Acquired Infections/ 9153

11 (airborne adj2 (transmission* or infection* or pathogen* or virus* or bacteria)).kf,kw,tw.
4399

12 *Skin/ 106343

13 "skin irri* ".kf,kw,tw. 5081

14 exp *Nervous System Diseases/ 2557769

15 exp *Fatigue/ 18793

16 exp *sensation disorders/ or *dizziness/ 154624

17 ("nervous system" or neurolog* or dizzy or dizziness or fatigue).kf,kw,tw. 895402

18 exp Educational Measurement/ 170709

19 Schools/ and Absenteeism/ 763

20 (school adj (absen* or truan* or attend*)).kf,kw,tw. 4445

21 ((educat* or school) adj2 (exam or result* or measure* or scor* or test*)).kf,kw,tw.
18365

22 *Influenza, Human/ 51468

23 (influenza or "flu").ti,kw,kf. or (influenza or "flu").ab. /freq=2 103838

24 or/1-23 5905922

25 (effect* or value or benefit* or outcome or impact or evaluation or intervention or
factor*).tw,kf,kw. 15260124

26 24 and 25 2741111

27 "EARLY INTERVENTION (EDUCATION)"/ or Program Evaluation/ or evaluation studies/ or
exp *"costs and cost analysis"/ or *"cost allocation"/ or *cost-benefit analysis/ or *"cost of
illness"/ or *health care costs/ or *health expenditures/ or Treatment Outcome/ or "Outcome
Assessment (Health Care)"/ or *"Outcome and Process Assessment (Health Care)"/ or
*Evidence-Based Practice/ or *quality assurance, health care/ 1686771

28 Public Health/mt [Methods] 4542

29 (effect* or value or benefit* or outcome* or impact* or evaluation* or intervention* or factor*).ti. or (effect* or value or benefit* or outcome* or impact* or evaluation* or intervention* or factor*).ab. /freq=3 7773770

30 or/26-29 9887070

31 *schools/ or *schools, nursery/ or *universities/ or *child day care centers/ or *nurseries, infant/ 44904

32 (nurseries or nursery or "day care" or creche or pre-school or preschool or kindergarten).kf,kw,tw. 63988

33 (school or college* or universit*).ti. or (school or college* or universit*).kf,kw. or (school or college* or universit*).ab. /freq=3 275067

34 (("primary school*" or "secondary school*" or "elementary school*" or "middle school*" or "high school*" or "sixth form") adj5 (campus or building* or facilit* or environment*)).kf,kw,tw. 965

35 (school adj2 (hall or assembly or dining or gym or room or class*)).kf,kw,tw. 3175

36 classroom.kf,kw,tw. 21648

37 ((Education* or learn* or campus or school or universit* or college) adj2 (build* or institution* or facilit* or environment*)).kf,kw,tw. 41900

38 or/31-37 389455

39 Air Pollution, Indoor/ or Environmental Monitoring/ or air conditioning/ or ecological systems, closed/ or exp *temperature/ or ventilation/ or *Dust/ or exp Asbestos/ or exp *Fungi/ or Humidity/ or environmental illness/ or sick building syndrome/ or environment, controlled/ or heating/ or humidity/ or lighting/ or exp Particulate Matter/ or Air Pollutants/ or exp *Carbon Dioxide/ or exp *Nitrogen Dioxide/ or exp *Allergens/ or *Volatile Organic Compounds/ or exp *Noise/ or exp *Sound/ 826185

40 ("IEQ" or "IAQ" or "Indoor environmental quality" or "indoor air quality" or "indoor air pollut*" or "indoor environment" or "building environment" or "building quality" or (Indoor adj4 (quality or pollution))).kf,kw,tw. 9550

41 "sick building".kf,kw,tw. 680

42 "thermal comfort".kf,kw,tw. 2239

43 "air conditioning".kf,kw,tw. 2871

44 ((indoor or building or environment* or classroom) adj5 (ventilat* or heat* or cool* or thermal or temperature or humid* or "carbon dioxide" or "Co2" or "Nitrogen dioxide" or "No2" or "Particulate Matter" or dust or asbestos or mold or mildew or chemical or Nois* or sound* or vibrati* or infrasound* or acoustic or "Volatile organic compound*" or "VOC")).kf,kw,tw. 74714

45 (radon or "allerg*").kf,kw,ti. or (radon or "allerg*").ab. /freq=2 170423

46 ("Heating Ventilation and Air Conditioning" or HVAC or "indoor lighting" or daylight or "natural light" or "artificial light").kf,kw,tw. 9664

47 or/39-46 1031043

48 30 and 38 and 47 3824

49 limit 48 to yr="1990 -Current" 3655

S4: Summary of literature and citations found in library search

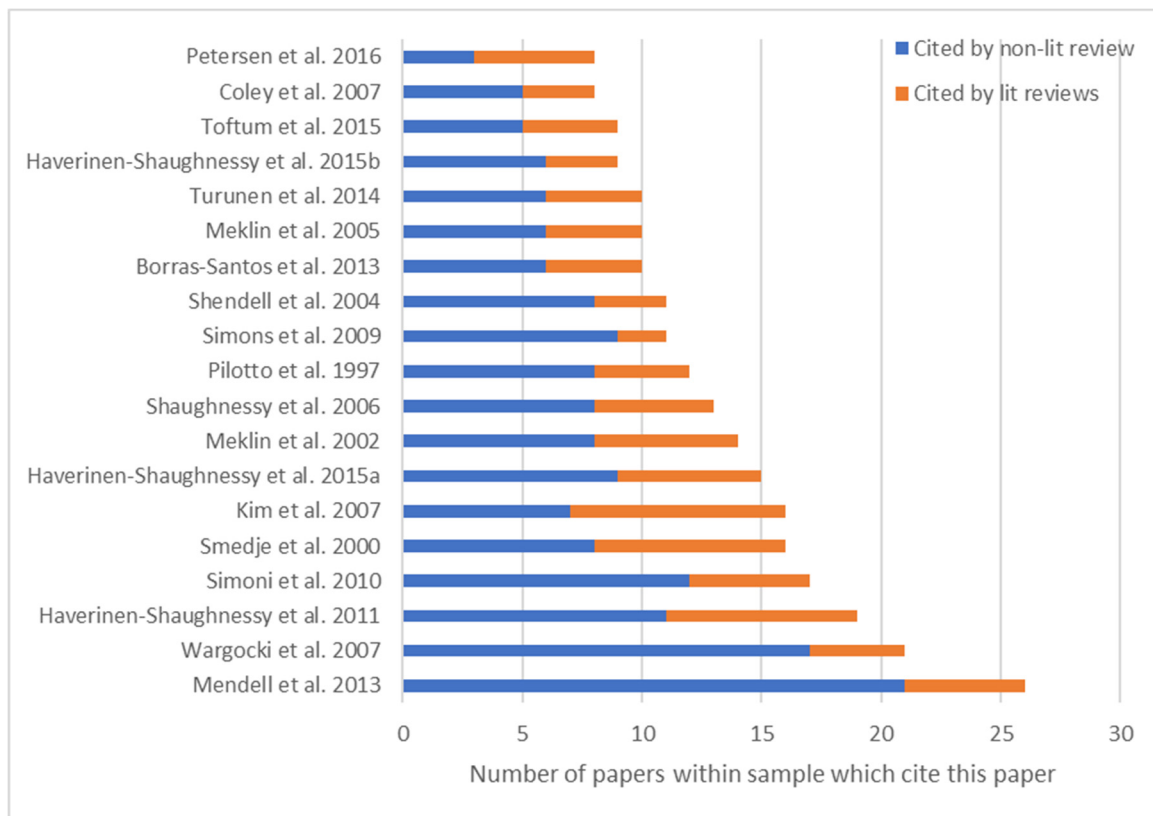


Figure S1: The most cited papers by other papers within the sample.

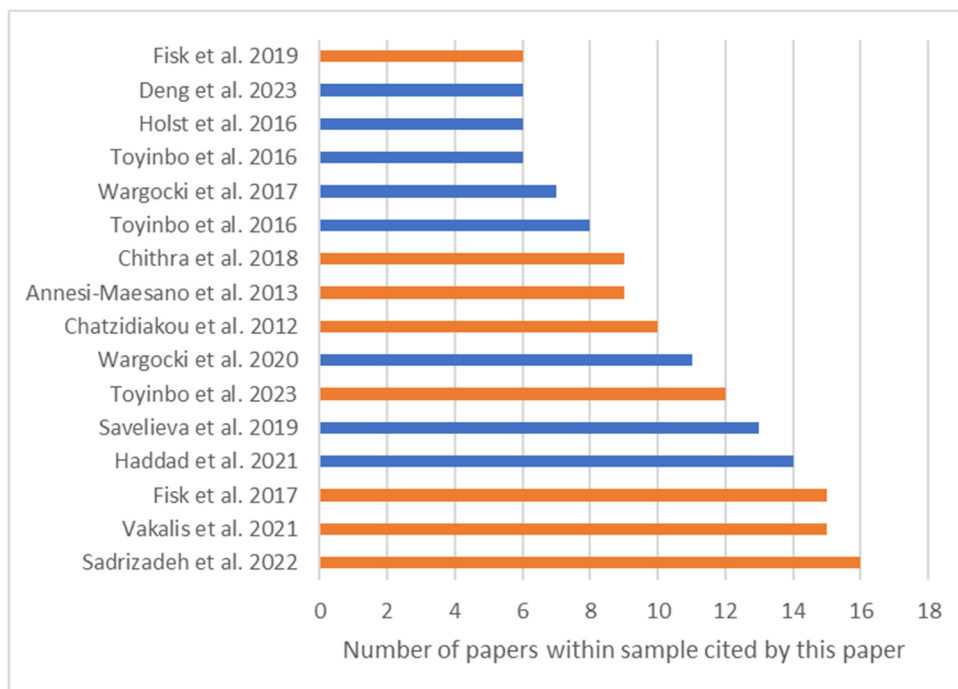


Figure S2: The papers which cite the most papers within this sample (orange indicating literature review, blue other studies)