MINISTRY OF EDUCATION
TE TĀHUHU O TE MĀTAURANGA

The Performance of Portable HEPA Air Cleaners in Naturally Ventilated Classrooms

A Systematic Literature Review

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Foreword

The New Zealand Ministry of Education's approach to addressing ventilation in schools, as part of its response to the COVID-19 pandemic has been informed by an evidence-based approach which includes this literature review.

In November 2021, the Ministry, in collaboration with the National Institute of Water and Atmospheric Research (NIWA) carried out a ventilation study, which confirmed that an efficient way of achieving good ventilation and reducing the transmission risk of COVID-19 is by opening doors and windows (i.e., natural ventilation).

In March 2022, the Ministry's Ventilation Programme in collaboration with the research institutes above carried out further studies. These include a control room study conducted at Epuni School and two literature reviews. This report is the second of the two literature reviews, and summarises the current research on the performance of portable air cleaners used in naturally ventilated classrooms for the purpose of COVID-19 mitigation.

The findings from these studies have informed our approach on managing ventilation in schools.

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Contents

Executive Summary 2

1.0 Introduction 3

2.0 Methodology 5

2.1 Identification of Alternative Terminology 5

2.2 Defining the Literature Databases, Search Rules and Screening Criteria That Were Used 6

2.3 Database Search 6

2.4 Final Screening 6

2.5 Inclusion Criteria 7

2.5.1 Relevant Literature 8

3.0 Literature Review 9

3.1 The Performance of Portable HEPA Air Cleaners in Naturally Ventilated Classrooms 9

4.0 Summary 12

5.0 Acknowledgements 13

6.0 References 14

7.0 List of Figures 13

6.0 List of Tables 14

Executive Summary

Increasing the supply of fresh air via natural ventilation is a good strategy for mitigating airborne COVID-19 transmission. This is particularly relevant to New Zealand, being that the majority of schools' classrooms are naturally ventilated. However, the effectiveness of natural ventilation is dependent on outdoor temperature and wind conditions, which are unable to be controlled. In situations where there are limitations which prevent or severely limit window-opening, either due to design or environmental conditions, the performance of natural ventilation can be compromised. In these cases, systems that assist ventilation can aid the performance of natural ventilation to achieve an appropriate amount of air changes, in order to mitigate COVID-19 transmission.

A well publicised method of providing additional airborne COVID-19 transmission mitigation alongside natural ventilation is the use of portable High Efficiency Particulate Air (HEPA) air cleaners/purifiers. Leading authorities confer that HEPA air cleaners are only to be considered a supplementary measure, second to fresh air ventilation as they do not affect CO_2 levels. The aim of this paper was to review the available literature on the performance of HEPA air cleaners in naturally ventilated classrooms.

Using the replicable search processes of a systematic literature review from medical research practice, 142 articles were retrieved from four search databases (ScienceDirect, Scopus, PubMed, and Google Scholar). Through analysis of these 142 articles, there were only seven articles that empirically investigated the methods of assisting natural ventilation in classrooms through HEPA air cleaners in the context of the COVID-19 pandemic. This demonstrates that there is a significant gap within the existing relevant literature, requiring further research to support them. The key findings were that:

- HEPA air cleaners that can achieve an effective air change rate of 5 – 6 per hour (eACH) have the potential to reduce the COVID-19 infection risk by 70 – 85%. However, this applies if there is only one infectious source and a single variant of COVID-19 present in the space. In order to achieve 5 – 6 eACH, a commercial grade air cleaner or multiple domestic-scale HEPA air cleaners each achieving 1 – 2 eACH is required.

- One study showed that partially opening windows during winter is more effective in reducing the risk of COVID-19 transmission than using two HEPA air cleaners each with a flow rate of 2.5 eACH in their optimal position. This was a simulation based study where natural ventilation was simulated as one-sided only, with six windows of 5.8 m^2 of openable area. A 60 cm opening represented being fully open and 20 cm represented being partially open, with a temperature differential (between the indoor and outdoor environments) of 17 °C during winter. The study also showed that HEPA air cleaners with a flow rate of 6 eACH can achieve a similar reduction in infection risk to natural ventilation.

- Multiple studies suggested the additive effect of using both HEPA air cleaners and natural ventilation. This was studied both in situ and through simulations and survey, in addition to infection risk measurements. They affirm that HEPA air cleaners can be used as an effective complementary measure in classrooms where natural ventilation is not adequate, and no other improvement measures are possible.

Summarily, the air changes from HEPA air cleaners are considered 'effective' (eACH) rather than 'actual' (ACH). This is because it does not move outdoor air to the interior of a building. Therefore, the use of HEPA air cleaners does not impact CO_2 levels and not a substitute for natural ventilation.

1.0 Introduction

The performance of naturally ventilated classrooms can be impacted by limitations which prevent or severely limit window-opening, either due to design, behavioural, or environmental conditions. A highly publicised method of providing supplementary airborne COVID-19 transmission mitigation alongside natural ventilation is HEPA air cleaners. HEPA air cleaners provide effective air changes per hour (eACH) by moving indoor air through a filter which can remove particulate matter, and any airborne particles with a size of 0.3 microns (μm) (EPA, 2022).

Governments and international organisations have a variety of guidance on the usage and deployment of HEPA air cleaners. These have been summarised below.

The World Health Organisation group schools into a 'non-residential' category and recommends that HEPA air cleaners can be used if natural ventilation is not adequate, and no other measure is possible. However, they also note that HEPA air cleaners are not a substitute for natural ventilation (WHO, 2021).

The Centers for Disease Control and Prevention recommend schools bring in as much outdoor air as possible. The use of HEPA air cleaners are predominantly recommended for areas deemed to be high-risk, such as nurses' offices (CDCP, 2021).

The Chartered Institution of Building Services Engineers supports the use of air cleaning technology as a part of the solution for reducing the risk of COVID-19 transmission. While their guidance is not specifically tailored for school environments, they noted that air cleaners do not address CO_2 concentration. Therefore, a primary focus should be on increasing levels of natural or mechanical ventilation (CIBSE, 2021).

The United States Environmental Protection Agency acknowledges the role that HEPA air cleaners can play in reducing the airborne transmission of COVID-19. Their specific recommendations for schools are only using air cleaners where ventilation is insufficient, as air cleaners alone cannot ensure sufficient air quality and so can only be considered a supplementary measure (EPA, 2022).

Ontario's Ministry of Education's advice for naturally ventilated classrooms is that window opening at intervals should be prioritised, but that all naturally ventilated learning spaces shall be equipped with HEPA air cleaner as a supplementary measure to natural ventilation (OME, 2021).

The Australian Health Protection Principal Committee recommends prioritising the optimisation of airflow through increasing natural ventilation. However, they acknowledge that some settings may not be able to achieve adequate natural ventilation and may require additional measures such as air cleaners (AHPPC, 2021).

The Welsh government has acknowledged air cleaners as supplementary measures for poorly ventilated spaces though not as individual stand-alone solutions (Welsh, 2022).

The above recommendations are based upon aspects of the current literature on the topic of the performance of HEPA air cleaners for COVID-19 mitigation within classrooms.

Though not included within this literature review due to the limit of empirical studies within the COVID-19 context, further supplementary measures have shown promising initial findings.

The method of assisted natural ventilation systems involves the installation of fans in or near the windows. This has been shown to allow spaces to reach the recommended ACH level for good Indoor Air Quality (IAQ) and reduce COVID-19 aerosols (Park et al., 2021; Ren et al., 2022).

When outdoor temperatures drop in winter, the ‘winter mode’ ceiling fans can be used in addition to natural ventilation to increase the supply of fresh air, while at the same time mitigating the effect on thermal comfort (Burridge et al., 2021; Lipinski et al., 2020).

Solar chimneys are ventilation assisting devices that are installed on the roof of a building and allow air to be heated by solar energy. They are designed to raise the temperature of ceiling level air in order to increase the temperature differential, leading to greater thermal comfort and airflow (Ma’bdeh et al., 2020).

Solar air heated ventilation units can provide passive heating assistance. This method can support natural ventilation without compromising thermal comfort (Trompetter et al., 2018).

These methods introduce areas for further research to be undertaken in the context of COVID-19.

This literature review explores the following research questions:

- *What is the performance of HEPA air cleaners in reducing the transmission risk of COVID-19 in classrooms?*
- *How does the performance of HEPA air cleaners both compare and add to natural ventilation?*

This paper builds on the earlier literature review by Sutherland et al., (2022) which focused on the impact of natural ventilation on thermal comfort.

2.0 Methodology

The methodology for the selection of publications followed the same process as described in Sutherland et. al. (Sutherland, 2022). The same pool of relevant literature was used due to the wide literature overlap between the two reviews; however different literature ranking was used. The methodology for the selection of publications followed the process outlined in Figure 1 below.

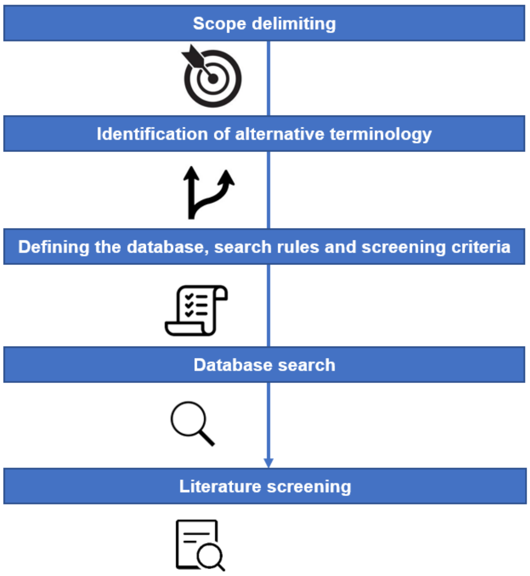

Figure 1. Process to select literature for this review

2.1 Identification of Alternative Terminology

After the scope of the literature review was established, a matrix of alternative terminology was created (refer Table 1 below).

Table 1: Keywords and alternative terminology

Natural Ventilation	School	Temperature	Effectiveness	COVID-19	Measures
Displacement ventilation	Classroom	Cold	Performance	SARS-CoV-2	HEPA
Cross-ventilation	Study room	Winter	Efficacy	Virus	Air cleaner and purifier
Ventilation	School room	Heating season	Value	Aerosol	Fan
Buoyancy driven flow	Teaching space	Low	Review	Transmission	Heat recovery
Convection	University	Weather			Assisted natural ventilation

2.2 Defining the Literature Databases, Search Rules and Screening Criteria That Were Used

The databases that were used were: PubMed, Scopus, Science Direct, and a general search on Google Scholar. These databases were chosen based on their science, architecture, engineering, and disease transmission coverage. To collate the literature the referencing software used was Mendeley. In terms of search rules, both peer-reviewed and grey literature were considered on an individual basis. This is due to the fast-evolving and urgent nature of this area of research. The limitations were that only papers that were available in English were used. Though the year of publishing was not a limitation, priority was placed upon literature from 2020 onwards, due to the importance, in this context, of the COVID-19 pandemic.

2.3 Database Search

The database search was conducted during the months of February and March 2022, using the search phrase and keywords noted above. From the initial search using the primary search phrase, 4,010 sources were found (see fig.2 below).

These searches included duplicates which were removed when identified throughout the screening process. These results were initially screened by their title to establish suitability, which resulted in 174 relevant papers. These papers were then screened through their abstract, which resulted in 113 relevant papers. From these 113 papers, 70 were deemed relevant after a full-text reading.

2.4 Final Screening

From the final 70 papers, a second search process was conducted through the original sources' reference lists. These papers were screened through their title and then a reading of their full text. This resulted in 72 additional papers being considered for this literature review (see Figure 2 below).

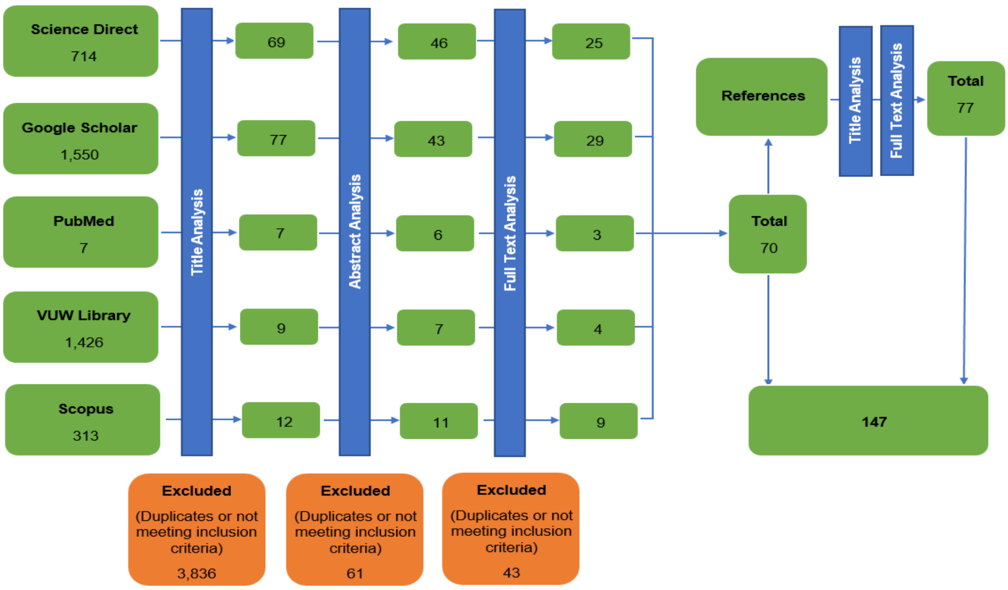

Figure 2. Sourcing diagram

2.5 Inclusion Criteria

The central purpose of this literature review was to investigate the performance of HEPA air cleaners in naturally ventilated classrooms in terms of COVID-19 transmission mitigation. Where there are limitations which prevent or severely limit window-opening, the performance of natural ventilation can be compromised. In these instances, HEPA air cleaners can be used as a supplementary measure.

Taking these objectives into account, this review focused on:

- Naturally ventilated school classrooms. Though mechanically ventilated classrooms were considered if it was not tested within the study i.e., considered a sealed room.
- In situ experiment studies and simulation studies.
- HEPA air cleaners' performance in terms of eACH, and COVID-19 transmission reduction.
- Studies which compared HEPA air cleaners' performance to natural ventilation and tested them in conjunction.

2.5.1 Relevant Literature

The following studies were ranked as 'most relevant' to this review's focus and are what the review is based upon.

Table 2: List of studies reviewed

Author/s	Title	Location	Typology	Type of Study	Measured
(Burgmann & Janoske, 2021)	Transmission and reduction of aerosols in classrooms using air purifier systems	Germany	School classroom	Experiment & Simulation	Transmission risk
(Curtius et al., 2021)	Testing mobile air purifiers in a school classroom: Reducing the airborne transmission risk for SARS-CoV-2.	Germany	School classroom	Experiment	Aerosol concentration, aerosol size distribution
(Duill et al., 2021)	The impact of large mobile air purifiers on aerosol concentration in classrooms and the reduction of airborne transmission of SARS-Cov-2.	Germany	School classroom	Experiment	Number of particles, particle size distribution, CO_2
(Lee et al., 2021)	Effect of air cleaner on reducing concentration of indoor-generated viruses with or without natural ventilation.	Korea	School classroom	Experiment	Age of air
(Lelieveld et al., 2020)	Model calculations of aerosol transmission and infection risk of COVID-19 in indoor environments	Germany	School classroom	Simulation	Infection risk
(Villers et al., 2021)	SARS-CoV-2 aerosol transmission in schools: the effectiveness of different interventions.	Switzerland	School classroom	Simulation	Mean cumulative dose, mean viral concentration
(Gettings et al., 2021)	Mask Use and Ventilation Improvements to Reduce COVID-19 Incidence in Elementary Schools —	Georgia	Schools	Survey	Compared COVID-19 incidence to prevention strategies implemented in schools

3.0 Literature Review

This section summarises the findings from the literature review.

3.1 The Performance of Portable HEPA Air Cleaners in Naturally Ventilated Classrooms

From the 142 papers reviewed, only seven papers empirically investigated the performance of HEPA air cleaners in naturally ventilated classrooms.

In Germany, Curtius et al., (2021) tested HEPA air cleaners in classrooms. The experiment consisted of up to four Philips (Model 2887/10) HEPA air cleaners being tested in situ within a classroom of 186.4 m^3. The study results indicate that if someone is in a closed room with a highly infectious person for two hours, the estimated reduction in transmission risk is 83% when using HEPA air cleaners that are achieving 5 -7 eACH. A limitation of this study was that it did not compare the performance of HEPA air cleaners with in situ natural ventilation. However, comparisons of the reduction in transmission risk using natural ventilation could be made with results from other studies. Additionally, similar performance of natural ventilation at an air change rate of 5 -7 eACH could also be inferred. However, these methods of comparison both have limitations due to not being tested under the same conditions. A further limitation is that in order to achieve 5 – 7 eACH a commercial grade air cleaner is required. An alternative is multiple domestic-scale HEPA air cleaners each achieving 1 – 2 eACH, as these are ones that are readily available. Furthermore, multiple air cleaner usage has acoustic consequences and may not be suitable for a classroom context.

In another German study, Duill et al., (2021) tested and simulated the performance of HEPA air cleaners in comparison to natural ventilation in a primary school classroom setting. The classroom's area measured 186 m^3 and three HEPA air cleaners were used to achieve 5 - 4 eACH. Four windows along one side of the classroom had (in total) 2.3 m^2 of openable area for natural ventilation, and a door on the opposite side was used to facilitate cross-ventilation.

Though the results from both this experiment and simulation indicate the improved performance of HEPA air cleaners in comparison to natural ventilation for the removal of potential viral particles, this study had multiple limitations including the introduction of pollen and other particles within the measured size range from natural ventilation. In addition, natural ventilation was only used at intervals (> 10 min), so the study cannot serve as a comparison for continuous natural ventilation.

In the third German study reviewed in this section, Burgmann & Janoske, (2021) both tested and simulated the effectiveness of HEPA air cleaners within a classroom occupied by 18 students. The classroom's area measured 197 m^3 and one HEPA air cleaner, which could achieve 6 eACH was used in different positions. The study findings suggest that the use of a HEPA air cleaner within a classroom could reduce the COVID-19 exposure risk by between 70% and 90% compared to a baseline test of no ventilation or HEPA air cleaner use. A limitation of this study is that it did not investigate the performance of natural ventilation as a comparison or HEPA air cleaners as a supplementary measure.

In the final German study reviewed, Lelieveld et al., (2020) simulated a scenario where a naturally ventilated classroom was equipped with HEPA air cleaners. The baseline active natural ventilation assumed to achieve 2 ACH. The HEPA air cleaner and natural ventilation used in combination was assumed to increase this to 9 eACH. The results from this modelling suggest that natural ventilation as simulated reduces the COVID-19 infection risk for classroom occupants by 58% when compared to the baseline, and around 90% with natural ventilation combined with the use of HEPA air cleaners.

This further supports the conclusions reached in other studies that additional performance improvements to COVID-19 transmission mitigation can be provided by HEPA air cleaners where they are used alongside natural ventilation. However, these results are very limited due to the set ACH rates given for natural ventilation when realistically this will vary significantly depending on factors such as temperature, wind speed, and openable areas.

In South Korea, Lee et al., (2021) both tested and simulated HEPA air cleaner's performance in a naturally ventilated classroom. The classroom in question measured 2 m^3 with six 1 m × 1 m windows and one 1.6 m^2 door. A Carrier CAP-D046WSA HEPA air cleaner with a flow rate of 285 m^3/h was used for this study. The initial 'age of air' measurements were taken within the classroom to verify the simulated model, which did not use any differential between the indoor and outdoor temperature. The findings of the experiment and simulation were that no matter the position of the air cleaner or direction of natural ventilation flow, the air was much fresher when both were used simultaneously. This suggests that HEPA air cleaners can be used as an effective complementary measure to natural ventilation in classrooms.

In Switzerland, Villers et al., (2021) adopted an existing COVID-19 aerosol transmission model to study the effects of risk mitigation measures of HEPA air cleaners, natural ventilation, face masks, and combinations of these measures. The model was simulated to represent a 160 m^3 classroom and one infectious individual. Natural ventilation was simulated as one-sided only, with each window being 0.96 m^2. With six windows being considered with a total of 5.8 m^2 of openable area they used two scenarios: one where 60 cm opening represented being fully open and the other where 20 cm represented being partially open. The indoor temperature was set at 22 °C with two temperature differentials modelled to represent summer months (18°C, differential of 4°C) and winter months (5 °C, differential of 17 °C).

The use of one or two HEPA air cleaners at a height of 1 – 1.8 m in the centre of the classroom was modelled using a flow rate corresponding to 2.5 ACH for each unit. The results of these simulations show that six windows partly opened at all times in winter reduces the mean cumulative dose of COVID-19 by 81.4%. This can be compared with a 2.5 eACH and 5 eACH HEPA air cleaner scenario which would result in a 59.3% and 74.2% decrease respectively. This suggests that partially opening windows during winter is more effective in reducing the risk of COVID-19 transmission than using two HEPA air cleaners in their optimal position.

In Georgia, 169 schools from 51 counties completed a survey provided by the Department of Education to assess COVID-19 prevention strategies implemented in schools at the time of the survey. These strategies included methods to dilute airborne particles by opening doors and windows, or using fans, or in combination with methods to filter airborne particles with HEPA air cleaners (with or without purification) (Gettings et al., 2021). The study found that COVID-19 incidence was 35% lower, in schools that improved ventilation through opening windows and doors, whereas in schools that combined opening doors and windows with HEPA air cleaners, incidence was 48% lower. The authors conclude that keeping doors and windows open and using fans to increase air flow from open windows are simple cost effective ways of improving ventilation. In rooms such as sick bay and offices that have an increased likelihood of being occupied by persons with COVID-19, or are difficult to ventilate installation of HEPA filters should be considered (Gettings et al., 2021).

From the seven papers reviewed above, three studies were both in situ experiments and simulations, two were only simulations, one was only an in situ experiment and one was a survey of COVID-19 prevention strategies implemented in schools. These studies generally agree that airborne transmission risk of COVID-19 can be significantly reduced with an air cleaner achieving an effective air change rate of approximately 5 - 6 eACH. Keeping doors and windows open is a simple cost effective way of improving ventilation, and in spaces that are difficult to ventilate combining opening windows and doors with HEPA air cleaners can reduce the transmission of COVID-19 in schools.

4.0 Summary

One of the most important findings of this literature review process is the identification of significant gaps within the body of literature on COVID-19 mitigation measures for naturally ventilated classrooms. The main gap is in situ experiments testing the performance of a variety of mitigation measures in a naturally ventilated classroom. Out of the seven studies reviewed in this literature review that focussed on HEPA air cleaners, none tested all of the following:

- In situ measurements of the HEPA air cleaner's performance in a naturally ventilated classroom.
- In situ measurements of the same classroom's natural ventilation performance.
- In situ measurements of the HEPA air cleaner and natural ventilation measured when they were used simultaneously.

A range of these experiments would be required to provide clear evidence that quantifies the performance of HEPA air cleaners in naturally ventilated classrooms, the comparative performance of natural ventilation, and the performance where they are used simultaneously.

In conclusion, this review has provided indications that:

- HEPA air cleaners that can achieve an effective air change rate of 5 – 6 per hour (eACH) have the potential to reduce the COVID-19 infection risk by 70 – 85%. However, this applies if there is only one infectious source and a single variant of COVID-19 present in the space. In order to achieve 5 – 6 eACH, a commercial grade air cleaner or multiple domestic-scale HEPA air cleaners each achieving 1 – 2 eACH is required.

- One study showed that partially opening windows during winter is more effective in reducing the risk of COVID-19 transmission than using two HEPA air cleaners each with a flow rate of 2.5 eACH in their optimal position. This was a simulation based study where natural ventilation was simulated as one-sided only, with six windows of 5.8 m^2 of openable area. A 60 cm opening represented being fully open and 20 cm represented being partially open, with a temperature differential (between the indoor and outdoor environments) of 17 °C during winter. The study also showed that HEPA air cleaners with a flow rate of 6 eACH can achieve a similar reduction in infection risk to natural ventilation.

- Multiple studies suggested the additive effect of using both HEPA air cleaners and natural ventilation. This was studied both in situ and through simulations and survey, in addition to infection risk measurements. The studies showed that HEPA air cleaners can be used as an effective complementary measure in classrooms where natural ventilation is not adequate, and no other improvement measures are possible.

Summarily, these studies agree that combining opening doors and windows with HEPA air cleaners can lower COVID-19 incidence in schools, and these are simple cost effective ways of improving ventilation.

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7.0 List of Figures

Figure 1. Process to select literature for this review 5
Figure 2. Sourcing diagram 6

8.0 List of Tables

Table 1: Keywords and alternative terminology 5

Table 2: List of studies reviewed 8