A systematic review of the mental health risks and resilience among pollution-exposed adolescents

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Abstract

Pollution is harmful to human physical health and wellbeing. What is less well established is the relationship between adolescent mental health – a growing public health concern – and pollution. In response, we systematically reviewed studies documenting associations between pollution and mental health in adolescents. We searched Africa Wide, Medline, PsycArticles, PsycInfo, PubMed, CINAHL, ERIC, SciELO, Scopus, and Web of Science Core Collection for studies published up to 10 April 2020 that investigated exposure to any pollutant and symptoms of anxiety; depression; disruptive, impulse-control, and conduct disorders; neurodevelopmental disorders; psychosis; or substance abuse in 10–24-year-olds (i.e., adolescents as per expanded and more inclusive definition of adolescence). This identified 2291 records and we assessed 128 papers for inclusion. We used a narrative synthesis to coalesce the studies' findings. This review is registered on PROSPERO, CRD42020176664.

Seventeen studies from Asia, Europe, the Middle East, and North America were included. Air and water pollution exposure was associated with elevated symptoms of depression, generalised anxiety, psychosis, and/or disruptive, impulse control and conduct disorder. Exposure to lead and solvents was associated with neurodevelopmental impairments. Most studies neglected factors that could have supported the mental health resilience of adolescents exposed to pollution. Notwithstanding the limited quality of most reviewed studies, results suggest that pollution exposure is a risk to adolescent mental health. High-quality research is urgently required, including the factors and processes that protect the mental health of pollution-exposed adolescents. Studies with adolescents living in low- and lower middle-income countries and the southern hemisphere must be prioritized.

Keywords: Multisystemic resilience; Psychopathology; Pollution; Systematic review; Young people

1. Introduction

Adolescent mental illness is widespread (Polanczyk et al., 2015). Most investigations of its aetiology – and related interventions – are focused on biological, psychological, and/or social determinants (Lund et al., 2018; Zwicker et al., 2020). Ecological determinants are often overlooked. Given growing attention to the intersectionality between environmental factors and adolescent health and wellbeing (Clark et al., 2020; Landrigan et al., 2019), disregard of ecological influences is problematic. This article interrogates the association between a specific environmental factor – pollution – and adolescent mental health. To that end, it systematically reviews empirical studies that examine the mental health of adolescents exposed to pollutants.

The focus on pollution – i.e., harmful substances, vibrations, heat, or noise that result from anthropogenic activity and contaminate the air, water, or soil (Office of the European Union, 2010) – relates to its consistent association with poorer physical health, including among adolescents (Clark et al., 2020; Landrigan et al., 2018; Ritchie and Roser, 2017). Pollution is also implicated in psychological distress and mental disorder (Marazziti et al., 2021). Various collaborative initiatives, such as the Sustainable Developmental Goals (e.g., Target 3.9) and the Paris Agreement (United Nations, United Nations), are in progress to reduce pollution. Even so, dangerous levels of pollution continue to threaten the health and wellbeing of most people worldwide (Shaddick et al., 2020).

Young people, especially those living in low- or middle-income countries (LMICs), are disproportionately vulnerable to pollution-related threats (Landrigan et al., 2019). Nevertheless, there has been little systematic attention to how those threats influence youth mental health. Prior reviews focus on children younger than 10 and/or narrowly on neurodevelopmental challenges (autism spectrum disorder, attention deficit hyperactivity disorder, impaired cognitive functioning) (Perera et al., 2019; Ventriglio et al., 2021). There is negligible consideration of mental disorders that typically have adolescent onset and have been reported for pollution-exposed adults, including depression, anxiety, or psychotic disorders (Marazziti et al., 2021). There is also scant consideration of how pollution exposure relates to other mental health difficulties that classically challenge adolescents (i.e., substance disorders; disruptive, impulse-control, and conduct disorders) (Lee et al., 2014; Rey, 2015). When adolescents (i.e., young people aged 10 to 24; Sawyer et al., 2018) were represented in the samples of studies included in systematic reviews, those reviews offered no adolescent-specific findings.

The abovementioned concerns spurred our systematic review of documented associations between pollution and adolescent mental health. Given concerns about inadequate researcher attention to what enables adolescent mental health resilience (Lund et al., 2018), we were also curious about what these studies might reveal about factors and/or processes that advance adolescents' resilience to pollution-related mental health threats. Thus, as per published protocol (Theron et al., 2021), four questions informed our review:

1. What is the association between adolescent pollution exposure and symptoms of adolescent mental illness?
2. In what ways, if any, are these associations different across adolescent development and diverse geographical contexts?
3. In instances where minimal symptoms of adolescent mental illness are reported, which protective factors, if any, are/could be associated with adolescent mental-health resilience to pollution exposure?
4. What clinical and/or study methodological characteristics might explain any heterogeneity in results?

2. Methods

This review was prospectively registered on PROSPERO (CRD42020176664) and published as a peer-reviewed protocol (Theron et al., 2021). Each step of the review was informed by PRISMA guidelines (Page et al., 2021).

2.1. Search strategy and selection criteria

Two authors (LS1 & LS2 [librarian]) searched for relevant academic journal publications discoverable via Africa Wide, Medline, PsycArticles, PsycInfo, PubMed, CINAHL, ERIC, SciELO, Scopus, and Web of Science Core Collection databases. Any quantitative, empirical study was eligible, provided it assessed both pollution exposure and mental health during adolescence and included some analysis of how these were linked in a human adolescent (age 10–24) sample. We subscribed to the European Union's (Office of the European Union, 2010) definition of pollution: i.e., harmful "substances, vibrations, heat or noise" that are emitted, via human activity, into the air, water or land. Knowing that neurodevelopmental disorders; disruptive, impulse-control, and conduct disorders; depressive disorders; anxiety disorders; substance disorders; and schizophrenia are typically associated with adolescents (Lee et al., 2014; Rey, 2015), we defined mental health as no/limited symptoms of these disorders. We excluded studies that did not measure mental health or exposure to human-produced pollutants. We also excluded studies that reported the use of man-made substances (e.g., solvents or pesticides) for self-harm purposes (e.g., suicide). We supplemented the database search with a backwards reference search of included studies and relevant reviews. Full information on the search terms and other search strategy aspects are detailed in the published review protocol (Theron et al., 2021), and the search terms for one data base are included in Supplemental File 2.

Search results were reviewed by at least two authors (LT, YAV, CB, MECL, GPA, MAO, LG, LL, IM, AT, KH). Based on title and abstract screening, each individually determined if the study met the inclusion criteria (i.e., any empirical study assessing associations between pollution exposure and the mental health of adolescents). Reviewer pairs resolved any discrepancies via consensus discussions; in the isolated instances of non-consensus, LT or KH arbitrated. Next, NG and SM independently read the full texts of selected studies to confirm their fit with the inclusion criteria (including that adolescent mental health outcomes and pollution exposure had been measured) or recommend exclusion. Discrepancies in their assessments (n = 11) were resolved by LT and KH, who independently reviewed the related articles.

2.2. Data extraction and quality assessment

LT and KH designed a data extraction form, which included the study's purpose, geographical context, design, sample (size and specifics), pollution exposure type and how that was measured/inferred, mental health outcomes and how they were measured, and factors (if any) that were associated with better mental health outcomes. They piloted the chart using 10 of the identified studies. NG and SM used the chart to independently extract data from all the included studies. LT and KH independently evaluated and refined that data extraction.

KH assessed the quality of evidence from included studies using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) (Guyatt et al., 2008), categorizing the papers as very low, low, moderate, or high quality. LT moderated that assessment. Following the Scottish Intercollegiate Guidelines Network (SIGN) guidelines and related methodology checklist (Healthcare Improvement Scotland), LT and KH independently assessed the risk of bias in the included cohort studies and used the Cochrane Collaboration Review Manager (RevMan) risk-of-bias graph to present these biases (Cochrane). All remaining authors reviewed, and confirmed, the extracted data and quality/bias assessments.

2.3. Data analysis

We conducted a narrative synthesis. Following Petticrew and Roberts (2006), we tabulated core details of the included studies, including pollution exposures and related mental health issues. We organised that content into pollution-specific categories; appraised the similarities and differences of within-category mental health outcomes; and considered across-category similarities and differences. Throughout this process, we took study design, quality, and bias into account. We did not pursue statistical analyses, given design variability and the diverse mental health outcomes.

2.4. Role of the funding source

Parts of the study were variously funded (see funding statement). These funders had no input into any aspect of the review, including the design, synthesis, or write-up.

3. Results

Our search yielded 2291 records, of which 2096 were screened after removal of duplicates. Of these, 17 were included in this review. The study selection is summarised as a PRISMA diagram (see Fig. 1). Key study details are summarised in Table 1. Below, we outline where the studies were conducted, the types of methods used, the pollutants examined, how pollution exposure was assessed, and the types of mental health outcomes measured, followed by patterns in the associations between pollution exposure and mental health.

Table 1. Key characteristics of included studies.

Authors	Study design	Study location	Adolescent sample characteristics	Exposure type and measurement	Mental health outcome of interest	Mental health measurement	Results	Quality of evidence
Ando et al. (2017)	Cross-sectional	Kochi Prefecture, Japan	*N* = 3040 51% male Age range: 12-15 M_{age} = 13.7, SD_{age} = 0.9	Lithium in tap water, measured through tap water samples	Depressive symptoms, suicidal ideation, aggressive behaviours	Self-report: Japanese version of the 12-item General Health Questionnaire [GHQ-12], 1-item self-designed dichotomous measure of suicidal ideation, 3-item self-designed measure of aggressive behaviours	Inverse association between lithium exposure and depression and aggressive behaviours. No association between exposure and suicidal ideation.	Low
Bang et al. (2017)	Nationally representative, cross-sectional, from the Korea Youth Risk Behavior Web-Based Survey	Republic of Korea	*N* = 62708 50.6% female Age range: 12–18 M_{age} = not provided, SD_{age} = not provided	Second-hand tobacco smoke, self-report survey of exposure in the past week and urine cotinine concentration	Depression, suicidal ideation, suicidal behavior	Self-report survey: 3 self-designed items (one item for each outcome)	Participants with second-hand smoke exposure had higher odds-ratios of having depression, suicidal ideation, suicidal planning, and suicidal attempt. There was a dose response effect, with those exposed to more second-hand having higher odds ratios.	Low
Bolle et al. (1996)	Three-year study with 2 timepoints	Geneva, Switzerland	*N* = 120 (*n* = 57 apprentice painters, *n* = 62 apprentices) 3.4% female Age range: 15-	Solvents (e.g., white spirit, toluene), exposure was determined based on apprentice trade	Neurodevelopmental disorder symptoms: short-term memory, perceptual coding, and cognitive ability	Cognitive assessments: Neurobehavioral Evaluation System translated to French	No differences between those exposed to solvents and not in neurodevelopmental disorder symptoms.	Very low

			20 M_{age} = 16.6, SD_{age} = 1.2					
Brunst et al. (2019)	Imaging study, nested in birth cohort study (Cincinnati Childhood Allergy and Air Pollution Study)	Cincinnati, Ohio, USA	N = 145 41.4% female Age range: 12 M_{age} = 12.2, SD_{age} = not provided	Traffic-related air pollution, measured through direct sampling with an estimate provided for exposure over the past 12 months	Total anxiety, as well as six subdomains of anxiety: panic/agoraphobia, social phobia, separation anxiety, obsessive-compulsive disorder, physical injury fears, and generalised anxiety	Self-report: 45-item Spence Children's Anxiety Sale (SCAS)	Significant positive association between pollution exposure and generalised anxiety symptoms. This association was mediated by significant myo-inositol increases. No associations between pollution and total anxiety or other subdomains of anxiety.	Moderate
Cossio-Torres et al. (2013)	Cross-sectional pilot study, sampled through the Childhood Lead Exposure Surveillance Program	Morales, San Luis Potosi, Mexico	N = 40 62.5% female Age range: 12–20 M_{age} = not provided, SD_{age} = not provided	Lead, measured through blood and bone. Mode of lead exposure not clear	Intellectual ability; symptoms of disruptive, impulse-control, and conduct disorders; alcohol- and tobacco-related substance use disorder symptoms	Clinical neurological examination; cognitive assessment: The Wechsler Intelligence Scale for Children (WISC-IV); self-report: The Alcohol Use Disorders Identification Test (AUDIT), Fargeström Test for Nicotine Dependence, Problem Oriented Screening Instrument for Teenagers (POSIT)	Lead exposure predicted lower intellectual ability and poorer perceptual reasoning. There were no associations with the other mental health outcomes.	Moderate

Hu et al. (2020)	Cross-sectional, convenience sample	Cities of Shenyang, Bengbu, Xinxiang, Ulanqab, Chongqing, & Yangjiang, China	*N* = 22,628 Age range: junior secondary to senior secondary school M_{age} = 15.36 SD_{age} = ±1.79	Second-hand smoke, self-report of exposure	Depressive symptoms, conduct disorder symptoms	Self-report: 39-item Multidimensional Sub-Health Questionnaire of Adolescent (MSQA)	Exposure to second-hand was associated with more mental health issues.	Low
Khorasanchi et al. (2019)	Cross-sectional, randomly selected sample	Mashhad and Sabzevar, Iran	*N* = 940 100% female Age range: 12–17 M_{age} = 14.6, SD_{age} = 1.6	Second-hand smoke, 1-item self-report survey of exposure	Intellectual ability, depressive symptoms, aggression	Cognitive assessments: Persian Cognitive Abilities Questionnaire; self-report: Beck Depression Inventory-II (BDI- II); the Buss-Perry Aggression Questionnaire (BPTQ)	Participants exposed to second-hand smoke had lower intellectual ability, as well as higher depressive symptoms and aggression than those not exposed to second-hand smoke.	Low
Kim et al. (2016)	Cross-sectional, baseline data from JS High School Study	Republic of Korea	*N* = 989 50% female Age range: high school freshmen M_{age} passive smokers = 15.5; M_{age} non-passive smokers = 15.3, SD_{age} = not provided	Second-hand tobacco smoke, self-report survey of exposure	Depressive symptoms	Self-report: Beck Depression Inventory-II (BDI- II	Participants exposed to second-hand smoke had more depressive symptoms. When split by sex, this association was significant for boys but non-significant for girls.	Low
Krieg et al. (2009)	Cross-sectional, National Health and Nutrition Examination Survey	United States	*N* = 8402 Male-female ratio not specified. M_{age} = not provided,	Lead measured via blood draw (unclear how exposure to lead occurred)	Neurodevelopmental disorder symptoms: intellectual ability	Cognitive assessments: Wechsler Intelligence Scale for Children-	Performance on all cognitive assessments was lower when blood lead levels were higher.	Moderate

	conducted from 1991 to 1994		SD_{age} = not provided Study includes adults and children, but we focus solely on the 12–16 year old analyses			Revised (WISC-R)		
Lee (2014)	Nationally representative, cross-sectional, from the 7th Korea Youth Risk Behavior Web-Based Survey	Republic of Korea	N = 75643 50% female Age range: high school M_{age} = 15.2, SD_{age} = 0.02	Second-hand tobacco smoke, self-report survey of exposure	Depression	Self-report survey: single self-designed dichotomous question	Participants exposed to second-hand smoke were more likely to indicate being depressed. There was a dose-response effect, with higher odds ratios among those exposed more days of the week.	Low
Manczak et al. (2020)	Longitudinal study with 2 timepoints (2 years apart), convenience sample	San Francisco Bay Area, USA	N = 110 49% female Age range: 11–15 at Time 2 M_{age} = not provided, SD_{age} = not provided	Water pollution (water contaminants, lead, nitrate, and arsenic), assessed within drinking water in census tract	Depressive symptoms	Self-report: Children's Depression Inventory (CDI)	Water contaminants, lead, and arsenic exposure were all positively associated with depressive symptoms. These associations were moderated by psychologically controlling family environment. Nitrate exposure was not directly associated with depressive symptoms, but there was a moderation by psychological control.	Moderate

Newbury et al. (2019)	Population-based, twin, cohort study (Environmental-Risk Longitudinal Twin Study)	England and Wales	*N* = 2063 52.5% female Age range:18 M_{age} = not provided, SD_{age} = not provided	Air pollution (NO_2; NO_x; $PM_{2.5}$ & PM_{10}), modelled for the participants' home address(es) and two other locations where they spent their time, assessed in 2012 when participants were 17	Psychotic experiences psychotic symptoms	Fieldworker interview, clinical verification	Participants exposed to air pollution levels (NO_2; NO_x; $PM_{2.5}$ & PM_{10}) in the top quartile had higher rates of psychotic experiences and psychotic symptoms than adolescents exposed to lower levels of pollution, although the associations did not hold for psychotic experiences or for PM_{10} and psychotic symptoms when all controls were added.	Moderate
Park (2017)	Nationally representative, cross-sectional study, from the 9th Korea Youth Risk Behavior Web-Based Survey	Republic of Korea	*N* = 56840, lifetime non-smokers 54.8% female Boys' M_{age} = 14.7, SD_{age} = not provided Girls' M_{age} = 14.9, SD_{age} = not provided	Second-hand tobacco smoke in the home, self-report survey of exposure	Depressive symptoms, suicidal ideation	Self-report survey: Two self-designed dichotomous questions, one each for depressive symptoms and suicidal ideation	Male and female participants exposed to second-hand smoke had higher levels of depressive symptoms and suicidal ideation than those without this exposure. There was a dose-response effect, with days of exposure positively correlated with depressive symptoms and suicidal ideation.	Low
Roberts et al. (2019)	Subsample of two timepoints from the population-based, twin, cohort study	London, UK	*N* = 284 46% female Age range: 12–18 (analyses focused on age 12 and age 18)	Air pollution (NO_2; $PM_{2.5}$), estimated based on kernel modelling for home address using	Depressive symptoms Anxiety symptoms Symptoms of disruptive, impulse-control, and conduct	Co-twin-, mother- and teacher-report of disruptive symptoms; clinical assessment; self-	At age 12, no concurrent associations between NO_2 or $PM_{2.5}$ and any of the mental health issues. Greater	Moderate

	(Environmental-Risk Longitudinal Twin Study)		M_{age} = not provided, SD_{age} = not provided	established inventories	disorders Neurodevelopmental disorder symptoms (specifically ADHD)	report: Children's Depression Inventory (CDI), Multidimensional Anxiety Scale for Children (MASC)	exposure to NO_2 and $PM_{2.5}$ at age 12 was associated with more depressive symptoms and also diagnosed depression at age 18. Exposure to NO_2 and $PM_{2.5}$ at age 12 was not linked to the other mental health symptoms or diagnoses at age 18, although it nears significance for a diagnosis of conduct disorder. There was a dose-response effect for depression, with those in the top quartile of NO_2 and $PM_{2.5}$ being 3–4 more likely to be diagnosed with depression than those in the bottom quartile.	
Saddik et al. (2005)	Cross-sectional study	Tripoli, Lebanon	N = 300 (n = 100 working with solvents, n = 100 working but not with solvents, n = 100 not working) 0% female Age range: 10-17 M_{age} working with	Solvents (used in automotive spray painting, mechanical repair, furniture painting)	Neurodevelopmental disorder symptoms: intellectual ability	Cognitive assessments: Draw a Person (DAP) test, Grooved pegboard, digit span from WISC-R	Those in the group who worked with solvents performed worse on the cognitive assessments, with lower overall complex cognitive function, slower motor coordination, and poorer memory.	Low

			solvents = 14.5, M_{age} not working with solvents = 14.7, M_{age} working with solvents = 14.0, SD_{age} = not provided					
Sui et al. (2018)	Cross-sectional	Anshan, China	N = 346 college students 100% female M_{age} = 19.87, SD_{age} = 1.46	Air pollution exposure, measured through time spent outside	Mental health (depression and anxiety symptoms)	Self-report: Symptom Checklist-90 (SCL-90)	Greater exposure to pollution over the past year and the past 30 days was associated with more mental health issues.	Very low
Zhao et al. (2019)	Cross-sectional analyses using data from 2 birth cohort studies (GINIplus and LISA)	Munich and Wesel, Germany	N = 2827 50.7% female Age range: 15 M_{age} = 15.20, SD_{age} = 0.30	Air pollution (ozone, NO_2, PM_{10}) long-term exposure and exposure over 0–7 days, estimated by home address using data from Umweltbundesamt	Depressive symptoms	Self-report: Depression Screener for Teenagers (DesTeen)	In the sample combining participants in Munich and Wesel, there were no associations between short-term exposure and depressive symptoms. There was one significant subgroup association: same day exposure to NO_2 and PM_{10} was associated with fewer depressive symptoms among participants in Wesel. There were no other associations by subgroup. There were no associations with long-term exposure.	Moderate

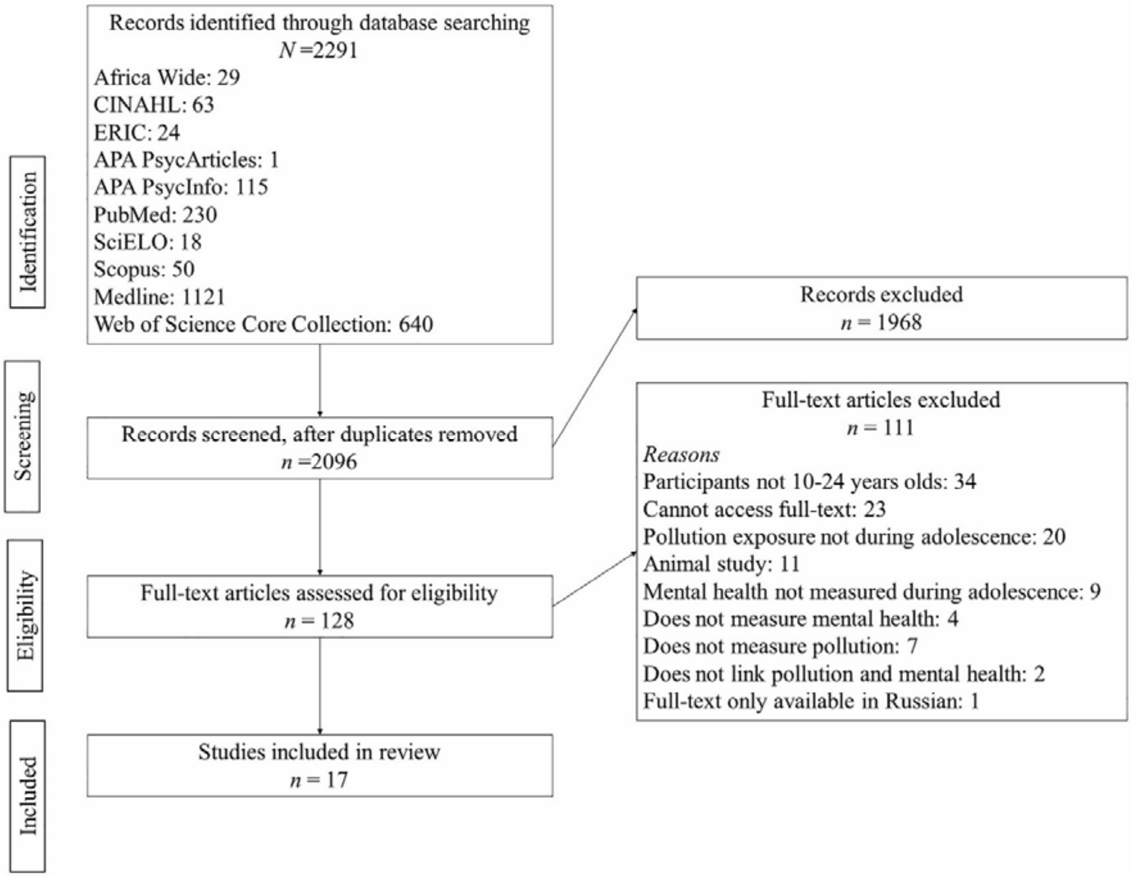

Fig. 1. Study selection.

Twelve studies were conducted in high-income countries (as defined by the World Bank) (World Bank): five in Asia (Ando et al., 2017; Bang et al., 2017; Kim et al., 2016; Lee, 2014; Park, 2017); four in Europe (Bolle et al., 1996; Newbury et al., 2019; Roberts et al., 2019; Zhao et al., 2019); and three in the USA (Brunst et al., 2019; Krieg et al., 2009; Manczak et al., 2020). The rest were conducted in upper middle-income countries in the Middle East (Khorasanchi et al., 2019; Saddik et al., 2005), Asia (Hu et al., 2020; Sui et al., 2018), and North America (Cossío-Torres et al., 2013). No included studies took place in Africa or South America or in any lower middle- or low-income country. Regardless of the income status of a country, household socioeconomic status (SES) can influence both likelihood of exposure to pollution and of developing mental health difficulties (Landrigan et al., 2018; Reiss, 2013); most (11) studies controlled for this by including SES as a covariate.

Included studies showed methodological heterogeneity, with 11 cross-sectional designs (Ando et al., 2017; Bang et al., 2017; Cossío-Torres et al., 2013, Hu et al., 2020, Khorasanchi et al., 2019; Kim et al., 2016, Krieg et al., 2009; Lee, 2014; Park, 2017; Saddik et al., 2005; ; Sui et al., 2018), 6 cohort designs (Bolle et al., 1996; Brunst et al., 2019, Manczak et al., 2020; Newbury et al., 2019; Roberts et al., 2019; Zhao et al., 2019), and sample sizes ranging from 40 to 75643. No sample was drawn from clinical populations. Only five samples were nationally representative (Bang et al., 2017; Lee, 2014; Park, 2017; Newbury et al., 2019; Roberts et al., 2019). Study quality was also variable (see Table 1), with seven rated moderate, eight low, and two very low. While diverse reasons informed these ratings (see Supplemental

Table 1), the studies' observational nature and inattention to dose-response effects were prominent limitations.

Eleven studies investigated ambient pollution, specifically second-hand tobacco smoke (Bang et al., 2017, Hu et al., 2020, Khorasanchi et al., 2019; Kim et al., 2016; Lee, 2014; Park, 2017); outdoor air toxins, including ozone, Nitrogen Dioxide (NO_2), Nitrogen Oxides (NO_x) and/or Particulate Matter ($PM_{2.5}$ and PM_{10}) (Newbury et al., 2019; Roberts et al., 2019, Sui et al., 2018; Zhao et al., 2019); and traffic-related air pollution (Brunst et al., 2019). Water pollution was less popular, with only two studies examining exposure to tap water polluted with arsenic, lead, lithium, or nitrate (Ando et al., 2017; Manczak et al., 2020). Two studies investigated trade-related solvent exposure without detailing the route of exposure (e.g., via solvent-contaminated water or air-inhalation) (Bolle et al., 1996; Saddik et al., 2005). Soil pollution was not examined in any study, although it was implicated in two studies of exposure to lead (Cossío-Torres et al., 2013, Krieg et al., 2009).

The methods used to assess pollution exposure were diverse. Six studies used adolescent or caregiver self-report measures (Bang et al., 2017, Hu et al., 2020, Khorasanchi et al., 2019, Kim et al., 2016; Lee, 2014, Park, 2017). Five estimated pollution exposure via participants' residential addresses or outdoor time (Brunst et al., 2019, Newbury et al., 2019; Roberts et al., 2019; Sui et al., 2018, Zhao et al., 2019). Two studies each sampled drinking water (Ando et al., 2017; Manczak et al., 2020), took x-rays and/or blood specimens (Cossío-Torres et al., 2013, Krieg et al., 2009), or assumed occupational solvent exposure (Bolle et al., 1996; Saddik et al., 2005). Pollution exposure duration was also disparate, with some studies measuring exposure for part of a day or a day (Hu et al., 2020, Khorasanchi et al., 2019); up to 7 days (Bang et al., 2017; Kim et al., 2016; Lee, 2014; Park, 2017; Zhao et al., 2019); a month (Cossío-Torres et al., 2013, Sui et al., 2018); a year (Brunst et al., 2019, Newbury et al., 2019; Roberts et al., 2019); and/or longer (Bolle et al., 1996 ; Manczak et al., 2020; Saddik et al., 2005, Zhao et al., 2019). Two studies did not specify exposure duration (Ando et al., 2017; Krieg et al., 2009).

Mental health outcomes were also heterogeneous. Eleven investigated depressive symptoms (Ando et al., 2017; Bang et al., 2017, Hu et al., 2020, Khorasanchi et al., 2019; Kim et al., 2016; Lee, 2014; Manczak et al., 2020, Park, 2017; Roberts et al., 2019; Sui et al., 2018, Zhao et al., 2019); four examined neurodevelopmental disorders (Bolle et al., 1996; Khorasanchi et al., 2019, Roberts et al., 2019, Saddik et al., 2005); three studied anxiety symptoms (Brunst et al., 2019, Roberts et al., 2019; Sui et al., 2018); and three investigated symptoms of disruptive, impulse-control, and conduct disorders (Hu et al., 2020, Khorasanchi et al., 2019, Roberts et al., 2019). Few studied symptoms of substance-related disorder (Bolle et al., 1996), or psychotic episodes (Newbury et al., 2019). There was preference for adolescent self-report to measure outcomes (Ando et al., 2017, Bang et al., 2017, Brunst et al., 2019, Hu et al., 2020, Kim et al., 2016, Lee, 2014, Manczak et al., 2020, Park, 2017, Sui et al., 2018, Zhao et al., 2019). (Ando et al., 2017; Bang et al., 2017; Brunst et al., 2019, Hu et al., 2020, Kim et al., 2016; Lee, 2014; Manczak et al., 2020, Park, 2017; Zhao et al., 2019; Brunst et al., 2019 Manczak et al., 2020;). Only four studies combined self-report with clinical or cognitive assessments, and/or parent-, twin- and teacher-report (Cossío-Torres et al., 2013, Khorasanchi et al., 2019, Newbury et al., 2019; Roberts et al., 2019). Predictably, studies that investigated intellectual functioning used cognitive assessment batteries (Bolle et al., 1996; Krieg et al., 2009; Saddik et al., 2005).

Most studies (14) reported significant positive associations between pollution exposure and adolescent mental illness, regardless of the pollutant investigated or the exposure duration (see Fig. 2). A minority found no association (Bolle et al., 1996; Zhao et al., 2019), or a significant inverse association (Ando et al., 2017).

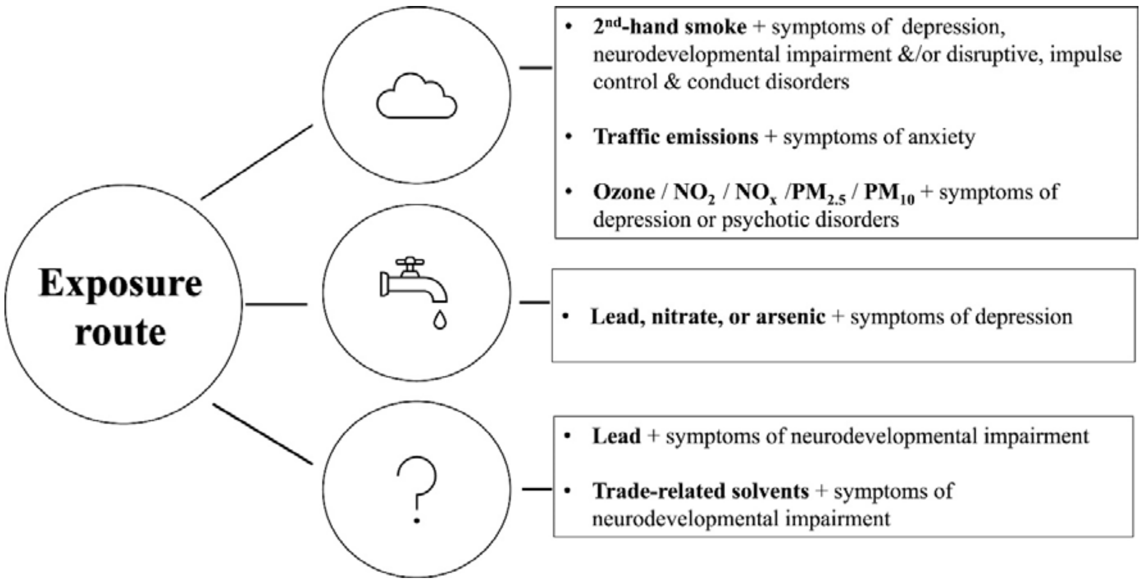

Fig. 2. Significant positive associations between pollutants and adolescent mental illness.

Second-hand smoke exposure – the most frequently investigated pollutant in included studies – was repeatedly associated with poorer mental health. Second-hand-smoke-exposed adolescents reported increased symptoms of depressed mood (Bang et al., 2017; Hu et al., 2020, Khorasanchi et al., 2019, Kim et al., 2016; Lee, 2014; Park, 2017), disruptive, impulse-control, and conduct disorder symptoms (Hu et al., 2020, Khorasanchi et al., 2019), or showed neurodevelopmental disorder symptoms (i.e., intellectual disability) (Khorasanchi et al., 2019). Three studies reported a dose-response effect (Bang et al., 2017; Kim et al., 2016; Park, 2017), with adolescents reporting more frequent exposure also reporting more depressive symptoms.

Exposure to other forms of air pollution – broadly termed traffic emissions or specifically as ozone, NO_2; NO_x; $PM_{2.5}$, and/or PM_{10} – was significantly positively associated with symptoms of depressed mood (Roberts et al., 2019); generalised anxiety disorder (Brunst et al., 2019); psychotic disorders, specifically delusions, hallucinations, unusual experiences (Newbury et al., 2019); and poorer general mental health, including depressive symptoms (Sui et al., 2018). Again, dose-response effects were noted (albeit in one study only) (Newbury et al., 2019), with adolescents in the top quartile of exposures to NO_2, NO_x, and $PM_{2.5}$ reporting higher rates of psychotic experiences. Adolescents in the top quartile of NO_2 and $PM_{2.5}$ exposure at age 12 were 3–4 times more likely to be diagnosed with depression at age 18 than adolescents in the bottom quartile. In contrast, Zhao and colleagues reported no significant association between depressive symptoms and adolescent exposure to ozone and residuals of NO_2 and PM_{10} in the German cities of Munich and Wesel (Zhao et al., 2019). Indeed, they reported a significant inverse subgroup association: same day exposure to NO_2 and PM_{10} was associated with fewer depressive symptoms among participants living in the city of Wesel. However, Zhao et al.

cautioned that this inverse relationship was probably a “chance finding”. (Zhao et al., 2019, p.78).

Adolescent exposure to water contaminated with lead, nitrate, or arsenic was positively associated with depressive symptoms (Manczak et al., 2020). However, the positive associations for lead and nitrate were moderated by a psychologically controlling family environment. Family environment did not moderate the association between arsenic and depression symptoms.

Predictably given its use as a mental health treatment, lithium-contaminated water was inversely associated with symptoms of depression and disruptive, impulse-control, and conduct disorder (Ando et al., 2017). Greater lithium exposure was associated with decreased depressive symptoms and less aggression.

Two studies investigated associations between lead and adolescent neurodevelopmental disorders, without specifying exposure routes (Cossío-Torres et al., 2013, Krieg et al., 2009). A small sample of adolescents (n = 40) who had lived in Morales, Mexico, since birth showed elevated blood levels of lead and symptoms of impaired neurodevelopment (i.e., intellectual disability) (Cossío-Torres et al., 2013). Likewise, symptoms associated with intellectual disability were reported for American adolescents with elevated blood levels of lead (Krieg et al., 2009).

Two studies investigated adolescent exposure to trade-related solvents (Bolle et al., 1996; Saddik et al., 2005). Solvents can enter the body via inhalation, water contamination, or through the skin. The cross-sectional study by Saddik and colleagues reported symptoms of impaired neurodevelopment (poorer cognitive functioning, slower motor coordination, and poorer memory) among Lebanese adolescents exposed to trade solvents (Saddik et al., 2005). The earlier cohort study by Bolle and colleagues found no significant relationship between trade solvent exposure and adolescent neurodevelopment (i.e., intellectual disability). (Bolle et al., 1996).

Except for Zhao and colleagues' cohort study with 15-year-olds living in German cities and exposed to ozone, NO_2 and PM_{10} (Zhao et al., 2019), the studies that investigated associations between air-borne pollution and adolescent depression symptoms all reported positive associations (Bang et al., 2017, Hu et al., 2020; Khorasanchi et al., 2019, Kim et al., 2016; Lee, 2014; Park, 2017; Roberts et al., 2019; Sui et al., 2018). Apart from Roberts et al. (2019), all studies reporting that positive association were cross-sectional, sampled adolescents from Asia or the Middle East, and assessed to be low- or very low-quality. Apart from (Hu et al., 2020), (Roberts et al., 2019), and (Sui et al., 2018), they all investigated exposure to second-hand tobacco smoke. Roberts and colleagues (Roberts et al., 2019), whose study was assessed as having moderate quality and low risk of bias (see Table 1, Table 2 and Supplemental Table 1), sampled a cohort of twins living in London, at age 12 and 18, and reported a significant association between NO_2 and $PM_{2.5}$ exposure and depression symptoms at age 18. Like Zhao and colleagues (Zhao et al., 2019), the Roberts et al. study used participants' residential details to estimate annual pollution exposure. In short, when compared with the cross-sectional studies outside of Europe (Bang et al., 2017, Hu et al., 2020; Khorasanchi et al., 2019, Kim et al., 2016; Lee, 2014; Park, 2017; Sui et al., 2018), it is possible that Zhao et al.'s discrepant finding could relate to location (i.e., a European country which highly regulates pollution exposure), longer exposure duration, mix of pollutants (ozone, NO_2 and PM_{10}) and/or methodological design. It is less easy to hypothesise why Roberts et al. and Zhao et al. reported contradictory findings,

Table 2. Risk of bias in included cohort studies.

	Clearly defined research question	Groups studied are comparable	Indicates who was asked to take part	Accounted for some participants having outcome at the start	Comparison between those retained and lost to follow-up	Outcomes are clearly defined	Assessment of exposure is reliable	Evidence from other sources demonstrates reliability and validity of assessment method	Exposure level is assessed more than once	Main potential confounds are included
Bolle et al., 1996	+	~	+	+	+	+	−	+	−	−
Brunst et al., 2019	+	+	+	−	+	+	+	+	+	+
Manczak et al., 2020	+	+	−	−	+	+	+	+	+	~
Newbury et al., 2019	+	+	+	−	+	+	+	+	+	+
Roberts et al., 2019	+	+	+	−	+	+	+	+	~	+
Zhao et al., 2019	+	+	+	−	+	+	+	+	+	+

+ indicates low risk of bias, ~ indicates unclear risk of bias, and − indicates high risk of bias.

Note: We assessed all papers on two additional criteria (assessment is blind to exposure, exposure status could influence outcome) but neither were applicable to any of the studies and so we have not included either in this table.

not least because their studies share contextual and methodological similarities (Roberts et al., 2019; Zhao et al., 2019).

The two solvent exposure studies that reported contradictory results were dissimilar in terms of sample, design, and location (Bolle et al., 1996; Saddik et al., 2005). The study reporting no significant association was conducted with Swiss adolescents aged 15 to 20; 57 were occupationally exposed to paint-related solvents and 62 not (Bolle et al., 1996). Cognitive functioning was measured at baseline and follow-up (3 years later). Only 32 solvent-exposed and 43 controls were available to follow-up. In contrast, the study reporting a positive association was cross-sectional and involved 300 Lebanese adolescents aged 10–17 (100 of whom were exposed to paint-related and other trade solvents; average age 14.5) (Saddik et al., 2005). Arguably, the variation in these studies' findings could relate to these methodological disparities. Both studies were rated poor quality; neither measured solvent exposure, instead assessing it indirectly based on likely exposure during work.

Beyond the obvious (i.e., exposure to no/limited pollution), studies did not explicate factors that protected the mental health of pollution-exposed adolescents. An exception was the finding of Manczak and colleagues that exposure to lead- and nitrate-contaminated water was only significantly associated with depression symptoms for adolescents from families who were psychologically controlling (Manczak et al., 2020).

4. Discussion

Unfortunately, the generally limited quality of included studies and instances of risk of bias limit what can meaningfully be said about the links between pollution exposure and mental health, and suggest that more, and more rigorous, studies are urgently needed. Relatedly, multiple determinants inform both pollution exposure and mental health difficulties (Lund et al., 2018; Marazziti et al., 2021). Because many of these are likely to overlap, causal links would be difficult to determine, even in high-quality studies. Nevertheless, the review results suggest that air and water pollution exposure (of any duration) is detrimental to adolescents' mental health, and is associated with elevated symptoms of depression, generalised anxiety, psychosis, and/or disruptive, impulse control and conduct disorder (see Fig. 2). Likewise, exposure to lead and solvents was associated with neurodevelopmental impairments. This range of mental health symptoms is a meaningful extension of earlier reviews that emphasized neurodevelopmental disorders and/or did not provide adolescent-specific findings (Freire and Koifman, 2013, Perera et al., 2019; Ventriglio et al., 2021).

Still, the range of mental health difficulties and pollutants was more limited than we expected. There were no eligible studies on noise or heat pollution, for instance, despite a large literature on their physical health impacts (Khan et al., 2018; O'Lenick et al., 2019). Although water pollution's negative physical health effects are well-established (Landrigan et al., 2018), we found only two eligible water pollution studies, and one was on 'positive' pollution impacts in the form of low-level lithium in the water. While substantial exposure to indoor air pollution is endemic in LMICs (Ritchie and Roser, 2017), no included paper measured indoor pollutants other than second-hand smoke. Few papers considered substance use or conduct disorder, despite these mental health issues often developing or worsening during adolescence. None included adolescents in Africa or South America, notwithstanding Africa having proportionally the highest number of adolescents worldwide (Unicef), and worrying pollution levels in both contexts (Katoto et al., 2019, Ritchie and Roser, 2017). Dose-response effects were underinvestigated, as were factors that mediate or moderate exposure. Relatedly, included papers were thin on factors that protected the mental health of pollution-exposed adolescents.

The most prominently reported significant association was between air pollutants (mostly second-hand tobacco smoke exposure) and depression symptoms. The emphasis on depression might relate to it being strongly implicated in impaired academic, physical, and social functioning among adolescents globally (Clayborne et al., 2019; Wickersham et al., 2021), and/or frequently reported in studies associating pollution exposure with adult mental illness (Marazziti et al., 2021). Although the study designs largely did not establish whether participants had been previously diagnosed with depression, being aware that adolescent depression is associated with pollutants suggests the need for action. One possibility would be large-scale psycho-education campaigns on the mental health benefits of avoiding and/or managing exposure to ambient pollution. Another would be to advocate for national and international health initiatives (e.g., the Global Strategy for Women's, Children's and Adolescents' Health, 2016–2030 (World Health Organisation); WHO's Comprehensive Mental Health Action Plan (World Health Organisation) to recognize pollution's potential to jeopardize adolescent mental health. Such recognition would mean that mental health concerns are added to the physical health/mortality ones that are typically listed as reasons for reducing pollution exposure.

Despite our quality-related concerns, practitioners, service providers and policymakers will better serve adolescents' mental health needs if they are sensitive and responsive to the probability of a positive relationship between pollution exposure and adolescent mental illness. The association between adolescent pollution exposure and multiple mental health difficulties amplifies the importance of better protecting youth from ecological risks, including anthropogenic ones (Clark et al., 2020), especially in adolescence when the onset of mental illness is most typical (World Health Organisation). Policy attentiveness to that relationship may have benefits for public health revenue and forestall losses related to disability-adjusted life years. Likewise, practitioners and service providers could consider enquiring about adolescent exposure to multiple harmful emissions – including exposures of shorter duration – and using this information to support potentially vulnerable adolescents in accessing mental health supports. Early diagnosis and timely, meaningful supports are associated with fewer disability-adjusted life years. Practitioners and service providers should also be mindful of what might have moderated exposure effects and work to sustain or augment those protective resources. The protective family environment finding reported by Manczak and colleagues encourages greater attention to what could support adolescents to avoid pollution-related mental health risks and nudges practitioners to leverage interpersonal resources in their efforts to advance the mental health resilience of pollution-exposed adolescents (Manczak et al., 2020). Following resilience theory's emphasis on multisystem supports mattering for mental health (Masten et al., 2021; Ungar and Theron, 2020), practitioner attention to interpersonal resources should be inclusive of intrapersonal and ecological resources that might buffer the negative mental health risks of pollution exposure. Practitioners are also well positioned to engage families, communities, and institutional representatives in psycho-education initiatives that support understanding that enabling physical environments are probably those that also protect adolescents from pollution exposure.

To better support practitioners and policy makers to identify malleable, multisystem resources that can be used to champion the mental health of pollution-exposed adolescents and mediate/moderate pollution impacts, future studies should incorporate an explicit resilience focus. That focus should include contextually relevant resources distributed across biological, psychological, social, institutional, and ecological systems and be attentive to their co-facilitative capacity to support mental health (Masten et al., 2021; Ungar and Theron, 2020). Future studies should also include direct assessment of pollution exposure, clinical or clinically validated measurements of mental health outcomes, and pre-registration of analyses. The type of pollutants included in this review need to enter the body to produce negative health effects, yet only three studies measured internal pollution exposure (Bang et al., 2017; Krieg et al., 2009; Cossío-Torres et al., 2013), limiting our understanding of the strength of pollution-mental health associations. The lack of experimental or quasi-experimental designs is also a substantial gap, not only to understand mental health risks, but also to evaluate health interventions that can be biased by factors that cause mental health problems (Vigo et al., 2016). Although an experimental design could prove an ethical challenge for some pollution exposures, it is possible for others (e.g., noise pollution). That all included studies were observational limits our understanding of potential mechanisms linking pollution exposure to mental health outcomes, and therefore the identification of intervention targets. Indeed, given the available evidence, we are unable to say if pollution exposure is causally linked with mental health impairments.

Our review was limited by the exclusion of publications in languages that were foreign to the review team (e.g., Russian). Further, despite repeated attempts, some full texts were inaccessible. Our decision to exclude studies that sampled adolescents and children/adults but offered no adolescent-specific results or which solely measured pollution exposure during childhood was necessary given the focus of our review (Theron et al., 2021). Had we decided differently, the review findings would have been inclusive of a wider range of pollutants, including noise pollution.

Despite these limitations, our study is the first to systematically review associations between adolescent pollution exposure and mental health. Although it draws on studies that were typically not high-quality, it nevertheless directs attention to the positive relationship that appears to exist between pollution exposure and adolescent reports of symptoms of a range of mental disorders. In a world where pollution levels and incidence of adolescent mental illness continue to raise substantial concern, (Clark et al., 2020; Shaddick et al., 2020; Unicef), high-quality studies of pollution-related determinants of adolescent psychopathology, and related policy and practice responses, are overdue. So too are studies of the factors and processes that moderate pollution's risk to adolescent wellness. In short, this review's take-home message is an urgent call to action for researchers, practitioners, and policymakers to better understand and better champion the mental health of pollution-exposed adolescents everywhere.

Data sharing

All data collected for this article, including data extraction tables, will be available from the publication date. Requests to access these data should be made to the corresponding author.

Authors' contributions

LT led the conceptualization of the review with input from all authors. LS1 and LS 2 conducted the data-base search; YAV, CB, MECL, GPA, MAO, LG, LL, IM, AT, KH, LT facilitated screening and initial study selection; NG, SM, KH & LT facilitated the final selection and data extraction. LT and KH conducted quality and bias assessments and analyzed the data; all other authors confirmed the analysis. LT and KH wrote the first and final drafts of the review. All other authors provided valuable editorial input to the drafts.

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Declaration of competing interest

We declare no competing interests.

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