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Association between exposure to wind turbines and sleep disorders: A systematic review and meta-analysis

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A R T I C L E I N F O

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A B S T R A C T

To date, there is scarce evidence on the association between sleep disorders and noise generated by wind turbines.

We searched six relevant electronic databases from the inception to May 2023 for relevant articles. The methodological quality of the included articles was evaluated using the US National Institutes of Health tool.

Fifteen articles met the inclusion criteria. The overall prevalence of sleep disorders among residents close to wind turbines was 34% (95% Confidence Interval, 0.22–0.47). Univariate meta-regressions for distance and sound power level showed that at higher distance the prevalence of sleep disorders decreases ($p = 0.010$) and with a higher sound power level the prevalence increases ($p = 0.037$). Furthermore, this systematic review and meta-analysis highlighted that the overall quality of current research on this topic is poor, and the methods to measure the results are often based on subjective assessments and not validated questionnaires.

In conclusion, our preliminary findings suggest that there may be a possible relation between exposure to wind turbines and sleep disorders, although no conclusions can be drawn in terms of causality due to the nature of the retrieved data and the poor quality of current evidence. Future studies should adopt a longitudinal design and focus on objective measurements, supported by validated subjective methods such as questionnaires.

1. Introduction

Over the past 15 years, European legislation has significantly promoted the development of renewable energy sources and set new targets and deadlines in order to answer the global increase in energy demand. The next commitment is to meet 32% of the energy needs through renewable energy by 2030, halve CO2 emissions compared to 1990, and move closer to near 100% independence from fossil fuels by the middle of this century. Despite the impact of the COVID-19 pandemic, renewable energy set a record for new power capacity in 2020 and was the only source of electricity generation to register a net increase in total capacity (REN21, 2021).

Wind energy is one of the fastest-growing renewable energy sources and the number of future plant installations is expected to substantially increase over the next few decades (Li et al., 2022). The wind energy industry recently enjoyed its second-best economic year, with almost 94 GW of installed capacity added, bringing the global wind power capacity to 837 GW, that is, up to 12% year-on-year growth. Europe played an important role in this growth, with new onshore installations increasing by 19% (GWEC, 2022).

The wind industry has confirmed its key role in the energy transition by presenting itself as one of the best technologies capable of ensuring compliance with international climate targets and reducing dependence on fossil fuels (Solarin and Bello, 2022). The wind is used to produce electricity by exploiting the kinetic energy of air moving through wind turbines (WTs) and other wind energy conversion systems. To ensure optimal efficiency, WTs are preferentially installed on hills, mountains, and in places that guarantee adequate convective conditions; however,

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these can also be placed in the open sea (the so-called offshore wind energy).

WTs are classified primarily based on their installation characteristics (onshore/offshore) and WT type (vertical/horizontal axis). The main difference between onshore and offshore wind farms is the foundation structure—while an onshore WT is based on concrete land, offshore turbines have foundations in water (floating) or on the seabed (fixed bottom). Compared to onshore WT, offshore wind power has the advantages of high wind speed, regional climate stability, and no significant visual impact; however, it has higher operating and maintenance costs and poor accessibility.

With the evidence of the various benefits of renewable energy sources over the last two decades, scientific research has focused on their potential environmental and health risks (Stefko et al., 2021).

Generally, wind energy has fewer environmental effects than other energy sources. WTs usually do not release air or water pollutants and do not require a water-cooling system. However, the reported impacts include changes in atmospheric conditions (Bodini et al., 2021) and accidental deaths of migratory birds colliding with the WTs (Katzner et al., 2017). In terms of possible human health effects, the noise produced by WTs is considered the main pollutant; however, other pollutants, such as vibrations and light contamination, could contribute to sleep disturbances. Furthermore, other issues such as noise sensitivity, visual impact, and landscape expectations can be considered as modifiers of the relationship between WTs exposure and health effects. The noise produced by the WT is both mechanical, owing to the friction of the rotor components and the generator transmission system, and aerodynamic, caused by the interaction of airflow with the blades (Lane et al., 2016). The WT blades moving through the air are capable of generating a broad spectrum of sounds, particularly low-frequency noise (LFN) in the range of 20–200 Hz, that can spread over long distances, potentially causing annoyance, sleep disturbances, and other adverse health effects (Smith et al., 2020). The latter include nausea, headaches, dizziness, fatigue, tinnitus, and cardiovascular symptoms (Turunen et al., 2021). The term "wind turbine syndrome" was coined by Pierpont (2009) to describe the association between these symptoms and exposure to WT noise.

Two previous systematic reviews and meta-analyses focused on sleep disorders in residents living near WTs plants (Liebich et al., 2020; Onakpoya et al., 2015). However, the results of these studies were inconclusive and partially contradictory. Specifically, Liebich et al. focused on studies reporting sleep outcomes in the presence of WTs using polysomnography and actigraphy and found that WT exposure did not affect key indicators of objective sleep. Onakpoya et al. analyzed self-reported sleep disturbance data and suggested that WT noise may be associated with increased odds of annoyance and sleep disorders. However, both studies concluded that there is a strong need for further evidence on this topic. Given the rapid technological development of this energy source and increasing worldwide spread, we considered it useful to update the results of previous studies focusing on subjective health assessment methodologies.

Therefore, given the relevance of this topic, the purpose of this systematic review and meta-analysis was to provide comprehensive data on the prevalence of sleep disorders among residents living near WTs and explore the possible associations between the distance from the WT and WT sound power levels.

2. Material and methods

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2015). We systematically searched for relevant articles in six electronic databases, including MEDLINE, PubMed, Embase, Cochrane Library, Web of Science, Scopus, and Reaxys from their inception to March 2022, and updated in May 2023.

2.1. Search strategy and study selection

The initial search strategy was exploratory and extensive and included studies on health outcomes, environmental issues, emissions, and experimental toxic effects of several renewable energy sources, such as biofuels, green hydrogen, solar power, carbon capture and storage, and nuclear fusion. Subsequently, a series of studies were conducted on the health outcomes of wind energy. Since health outcomes other than sleep disorders were sparse and highly heterogeneous, we decided to focus only on articles on sleep disorders. The search strategy was first executed on PubMed and then adapted for all databases. The following example search terms were used: "Wind" [Mesh], ("wind power" [Tiab, "wind turbine*" [Tiab], "wind farm*" [Tiab], "wind resource*" [Tiab], "wind energ*" [Tiab], "wind plant*" [Tiab]. An expert librarian was involved in database searches to ensure methodological rigor. Reference lists of the included articles were manually selected to identify other relevant articles.

Two researchers independently evaluated titles and abstracts. After the initial selection, two investigators independently evaluated the full text for potentially relevant articles. Any disagreements were resolved by consensus among the investigators or with the help of a third reviewer.

2.2. Inclusion and exclusion criteria

This systematic review and meta-analysis included data on sleep disorder rates among residents living in a wind farm area from cross-sectional investigations. The included articles investigated the presence of sleep disturbance using various questionnaires and tools. Despite methodological differences between studies, all examined the prevalence of sleep disorders related to noise exposure for subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and/or daytime dysfunction. No restrictions were applied for sound power level or distance from the dwellings. Similarly, no restrictions were applied to network connections or WT types.

Workers were excluded because of their different exposure patterns compared with residents and uncomparable results in terms of sleep disturbance. Offshore installations were excluded because they were a source of exposure mainly to workers and had less effect on onshore residents.

Only the articles published in peer-reviewed journals were included. Experimental studies, systematic reviews or meta-analyses, conference proceedings, theses, and letters to the editor were excluded. Articles for which the full text was not available online or upon request from the journal were excluded. Language exclusion criteria were not applied.

For multiple reports from the same sample, the most complete results (i.e., those based on the largest number of cases) were used.

2.3. Data extraction

In each study, the number of residents with sleep disorders was used as the primary outcome measure. 'Sleep disorders' is an umbrella term including sleep disturbance, poor sleep quality, insomnia, and restless leg syndrome (Karna et al., 2022). If more than one disorder was considered, the data with the highest prevalence for each disorder were used as the main outcome.

When prevalence rates were not directly reported, the results were extrapolated from the retrieved questionnaire scores. Residents with scores >5 on the Pittsburgh Sleep Quality Index (PSQI), or ≥ 6 on the Athens Insomnia Scale (AIS) were considered affected by a sleep disorder. Moreover, for studies that used a single question to assess perceived sleep quality, we used the same criteria adopted by the authors to identify residents reporting sleep disorders. Furthermore, if reported in the study, the data were stratified according to the distance from the WT ($<$500 m, 500–1000 m, 1000–1500 m, and $>$1500 m) and outdoor Aweighted sound power level (SPL; <30 dB, 30–35 dB, 35–40 dB, 40–45 dB, and >45 dB).

The following study characteristics were extracted if reported in the article: publication year, country, study design, cohort size, sociodemographic characteristics of the respondents, number of wind farms, number of WTs, and WT power. Data were extracted by three independent reviewers, and any disagreements were resolved by a fourth reviewer.

2.4. Quality assessment

The methodological quality of articles was assessed using the National Institutes of Health Quality Assessment Tool (NIH, 2014). As the assessment tool did not provide cut-off values, the median score (median = 8) was calculated to define poor (score = 4–7), fair (score = 8–10), or good (score = 11–12) quality articles. Quality assessment was performed by three independent reviewers and the results were discussed with a fourth reviewer until a consensus was reached.

2.5. Statistical analysis

All analyses were performed using STATA SE/17 (StataCorp LLC, College Station, TX, USA) to estimate pooled mean effects and 95% confidence intervals (CI) using random-effects models. Before conducting the overall pooled prevalence meta-analysis, the heterogeneity of the prevalence estimates was evaluated by calculating the I^2 index and performing Cochran's Q test. An $I^2 > 50\%$ and Cochran's Q test p-values <0.05 represented a high degree of heterogeneity.

As high heterogeneity was expected due to the study design, random-effects meta-analyses with 95% CI were performed. Because the random-effects model resulted in a high mean square error in highly heterogeneous meta-analyses, a series of meta-analyses stratified by study quality was also performed. This assessment provided more robustness and led to the correct interpretation of the probability of coverage of the confidence interval regardless of heterogeneity. As the data were not normally distributed, a Freeman-Tukey double arcsine transformation was used to obtain the proportions collected from the included articles. This approach was used to stabilize variance in the data (Barendregt et al., 2013; Nyaga et al., 2014).

Subgroup meta-analyses were performed for distance and SPL. We performed a series of meta-regressions to examine the association between environmental factors and the prevalence of sleep disorders. We used a best-fit model to describe the relationship between sleep disturbances, the distance between dwellings and the WTs, and SPL.

We evaluated the presence of publication bias and small study effects by visual inspection of funnel plots and through a test proposed by Egger et al. (1997). Sensitivity analyses included repetitions of the main meta-analysis in which one article was removed to observe any effects.

3. Results

The exploratory database search yielded 12,242 articles. The initial screening of titles and abstracts, aimed at selecting articles related to health effects, and 618 articles were potentially relevant to our search. A manual reference search identified additional 171 potentially relevant studies. After duplicates were removed, 206 articles remained. These

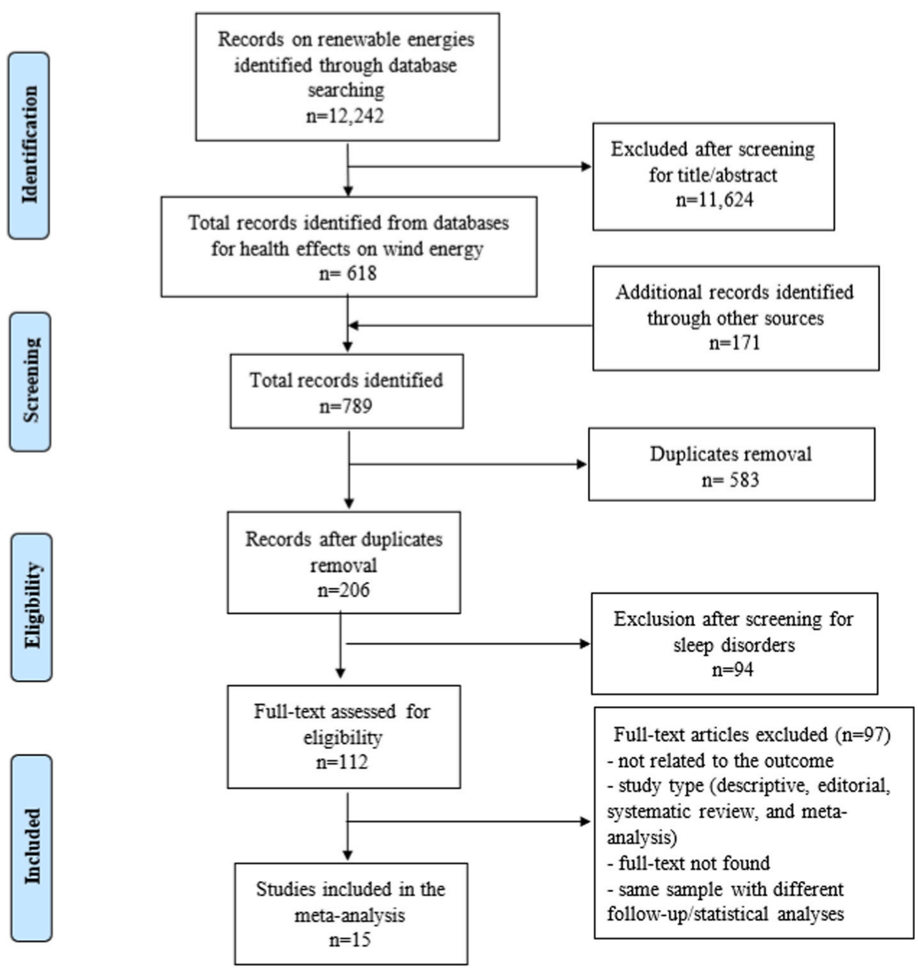

Fig. 1. Flow diagram for study selection.

articles were further screened to select those that were specifically relevant to sleep disorders. Thus, 110 studies were considered relevant for inclusion. The full texts of these articles were examined in detail and assessed according to the inclusion and exclusion criteria. Finally, 15 articles (Bakker et al., 2012; Ishitake et al., 2019; Jalali et al., 2016; Krogh et al., 2011; Magari et al., 2014; Michaud et al., 2016; Mroczek et al., 2015; Nissenbaum et al., 2012; Pawlaczyk-Łuszczyńska et al., 2018; Pedersen and Persson Waye, 2004; Pedersen and Waye, 2007; Qu and Tsuchiya, 2021; Song et al., 2016; Turunen et al., 2021a; 2021b) were included in the final analysis. The screening process is illustrated in Fig. 1.

Most studies were conducted in Europe (n = 8), followed by the United States and Canada (n = 5), Asia and Australia (n = 2). The selected articles were published between 2004 and 2021. In total, the data of 8,867 participants were analyzed.

All the studies evaluated subjective sleep quality using self-reported measures. Eleven studies used a single question to assess perceived sleep quality, whereas the remaining four studies adopted validated questionnaires. In particular, three studies used the PSQI, which measures seven components of self-perceived sleep quality (i.e., sleep quality, latency, duration, efficiency, disturbance, use of sleep medication, and daytime disturbance), and AIS, designed to measure the severity of insomnia symptoms.

The distance between the dwellings and WTs ranged from 495 to 3,093 m. The number of WTs ranged from 16 to 1,836 and their powers ranged from 0.5 to 3.5 MW. The mean SPL measured using A-weighting curves ranged from 33.4 dB to 42.6 dB. Four studies (Bakker et al., 2012; Ishitake et al., 2019; Michaud et al., 2016; Song et al., 2016) reported the prevalence rates of sleep disorders stratified by SPL, and three (Ishitake et al., 2019; Krogh et al., 2011; Nissenbaum et al., 2012) were stratified by distance from the WTs.

The mean age of the study participants, among the 13 studies, was

Table 1
Main findings of studies on sleep disorders.

Study	Country	Respondents	Age	Sleep disorders (Type of assessment)	Other outcomes investigated	Study Findings
Bakker et al. (2012)	Netherlands	725	52	Subjective sleep quality (Single question[b])	Annoyance	Sleep disturbance increased with SPL, especially above 45 dB (A), where 48% of the respondents reported sleep disturbance.
Ishitake et al. (2019)	Japan	2,192	58.1	Insomnia (AIS)	Annoyance	Audible noise (frequency of 20 Hz or over) produced by WTs can be a risk factor for sleep disorders
Jalali et al. (2016)	Canada	37	54	Subjective sleep quality (PSQI)	General attitude	Participants reported poorer sleep quality if they had a negative attitude toward WTs
Krogh et al. (2011)	Canada	97	52	Subjective sleep quality (Single question[c])	QoL, Signs and symptoms	Dose–response relationships between sleep disturbance, excessive tiredness, and headaches and distance from WTs
Magari et al. (2014)	US	62	51	Subjective sleep quality (Single question[b])	General attitude Annoyance Visual impact	No exposure-response relationship between annoyance levels and sound measurements. Positive correlation between general concerns about health effects and prevalence of sleep disturbances.
Michaud et al. (2016)	Canada	1,208	–	Subjective sleep quality (PSQI) Objective sleep quality (Actigraphy)	–	The results of the study do not support an association between exposure to outdoor WT noise up to 46 dB(A) and an increase in the prevalence of disturbed sleep.
Mroczek et al. (2015)	Poland	1,277	45.5	Subjective sleep quality (Single question[c])	QoL	The WTs in residential areas do not have a negative influence on quality of life. Sleep disorders were reported by 28.34% of the respondents.
Nissenbaum et al. (2012)	USA	38	–	Subjective sleep quality (PSQI)	QoL	Participants living within 1.4 km of a WT had worse sleep. Significant dose-response relationships between PSQI, ESS, SF36 mental component score, and log distance to the nearest WT were identified.
Pawlaczyk-kuszczyriska et al., (2018)	Poland	517	46.7	Subjective sleep quality (Single question[b])	Annoyance General attitude Mental health	There was no significant association between SPL/distance and various aspects of health.
Pedersen and Waye, (2007)	Sweden	754	51	Subjective sleep quality (Single question[b])	Sensitivity to noise Annoyance	Noise annoyance was associated with sleep quality and negative emotions. The odds of being annoyed by wind turbine noise also increased with increasing SPLs.
Pedersen and Persson Waye, (2004)	Sweden	351	48	Subjective sleep quality (Single question[b])	Sensitivity to noise Annoyance Visual impact	No correlations were found between sleep quality in general and outdoor noise, annoyance, indoor noise annoyance, attitude to visual impact and to WTs in general, or sensitivity to noise.
Qu and Tsuchiya, (2021)	UK	359	56	Subjective sleep quality (Single question[a])	QoL, Signs and symptoms	The WT noise was associated with some aspects of self-reported health, including raised health concerns, headaches, nausea, and ear discomfort, but was not directly related to sleep disturbances.
Song et al. (2016)	China	227	57	Subjective sleep quality (Single question[b])	Sensitivity to noise Annoyance	Noise sensitivity, noise annoyance, and noise intensity were significantly correlated with sleep disturbance.
Turunen et al. (2021a)	Finland	70	59	Subjective sleep quality (Single question[b])	Annoyance Signs and symptoms	Symptoms intuitively associated with wind turbine infrasound were relatively common (15%) within 2.5 km of the closest wind turbine and less common (5%) in the whole study area.
Turunen et al. (2021b)	Finland	1,180	60	Self reported[b]	Annoyance Signs and symptoms	Beyond annoyance and disturbance of sleep, there were no consistent associations between wind turbine exposure and self-reported health problems.

Abbreviations: AIS Athens Insomnia Scale, PSQI Pittsburgh Sleep Quality Index, WT Wind Turbine, QoL Quality of life; SPL Sound Power Level, dB Decibel, SF-36 Short Form Health Survey 36, GHQ-12 General Health Questionnaire 1

[a] Self-reported single question on presence of sleep disturbances (6-point Likert-type scale).
[b] Self-reported single question on presence of sleep disturbances (5-point Likert-type scale).
[c] Self-reported single question on presence of sleep disturbances (Yes vs No).

53.04 (SD ± 4.75). The number of respondents ranged from 37 to 1,965. Other sociodemographic characteristics such as marital status, smoking habits, and alcohol consumption were only occasionally reported.

The characteristics of the included studies, along with a summary of the main findings, are summarized in Table 1.

A complete quality assessment is reported in the Supplementary Material (Table S1). Two articles were of high quality, eight were of poor quality, and the remaining five were of fair quality.

3.1. Meta-analyses and meta-regression

The overall prevalence of sleep disorders among residents close to WTs was 34% (95% CI, 0.22–0.47) (Fig. 2).

The prevalence of sleep disorders among residents living <500 m from WTs was 79% (95% CI, 0.58–0.93), while the sleep disorders rates in the intervals 500–1000, 1000–1500, 1500–2000, 2000–3000, >3000 were, respectively, 65% (95% CI, 0.36–0.89), 41% (95% CI, 0.34–0.48), 29% (95% CI, 0.24–0.33), 22% (95% CI, 0.19–0.24), and 27% (95% CI, 0.22–0.33).

The lowest prevalence of sleep disorders was found at SPL <30 dB (31%; 95% CI, 0.17–0.46). Progressively higher rates were found at higher dB intervals as follows: 36% (95% CI, 0.25–0.48) at 30–35 dB, 49% (95% CI, 0.28–0.69) at 35–40 dB, 60% (95% CI, 0.22–0.92) at 40–45 dB, and 82% (95% CI, 0.75–0.88) at >45 dB.

Univariate meta-regression for distance (Ishitake et al., 2019; Krogh et al., 2011; Nissenbaum et al., 2012) and SPL (Bakker et al., 2012; Ishitake et al., 2019; Michaud et al., 2016; Song et al., 2016) showed that at a higher distance, the prevalence of sleep disorders decreased ($p = 0.010$) (Fig. 3a) and with a higher SPL, the prevalence increased ($p = 0.037$) (Fig. 3b).

3.2. Sensitivity analyses

The omission of any single study from the main meta-analysis did not significantly influence the pooled prevalence of sleep disorders, with a maximum variation of 3% in the outcome ($p < 0.01$). Furthermore, the meta-analysis performed after excluding low-quality articles did not show a significant difference in the prevalence rate, with an overall prevalence of sleep disorders of 31% (95% CI, 0.19–0.44). Univariate meta-regression of the quality scores revealed no significant association with the prevalence of sleep disorders.

The funnel plot for the overall meta-analysis was scattered and asymmetrical, indicating the presence of reporting bias (Supplementary Material, Fig. S1). Similarly, the results of Egger's test were statistically significant ($p < 0.05$) for the presence of a small study effect.

4. Discussion

This systematic review and meta-analysis investigated the prevalence of sleep disorders among residents living near WTs. Our results showed an overall prevalence of 34% in all the included studies. The actual impact of WTs noise exposure on the development of this disturbance is difficult to address given the possible exposure to other environmental sources of noise and the presence of many confounders and modifiers that can affect the prevalence of sleep disorders.

4.1. Sleep disorders in the general population

Several epidemiological studies have attempted to determine the prevalence of sleep disorders in the general population. An international survey by Leger et al. (Léger et al., 2008) conducted on a representative sample of the general population of the United States, France, Germany, Italy, Spain, the United Kingdom, and Japan, aged ≥15 years, showed that the prevalence of sleeping problems was 56% in the USA, 31% in Western Europe, and 23% in Japan. A recent article by Jahrami et al. (2021) published during the COVID-19 pandemic, highlighted that the global pooled prevalence rate of sleep problems among all included populations was 35.7%. As shown by the authors, there are consistent variations in the prevalence of sleep disorders in the general population (Jahrami et al., 2021). These variations could be explained by clinical and epidemiological difficulties in defining the diagnostic criteria for sleep disorders and, as a result, the heterogeneity of these definitions. Additionally, the inclusion criteria considered by different authors vary widely, and environmental noise exposure has been poorly reported. Other concerns regarding sleep disorders include a diagnosis not obtained by a specialist and the application of different scales to measure

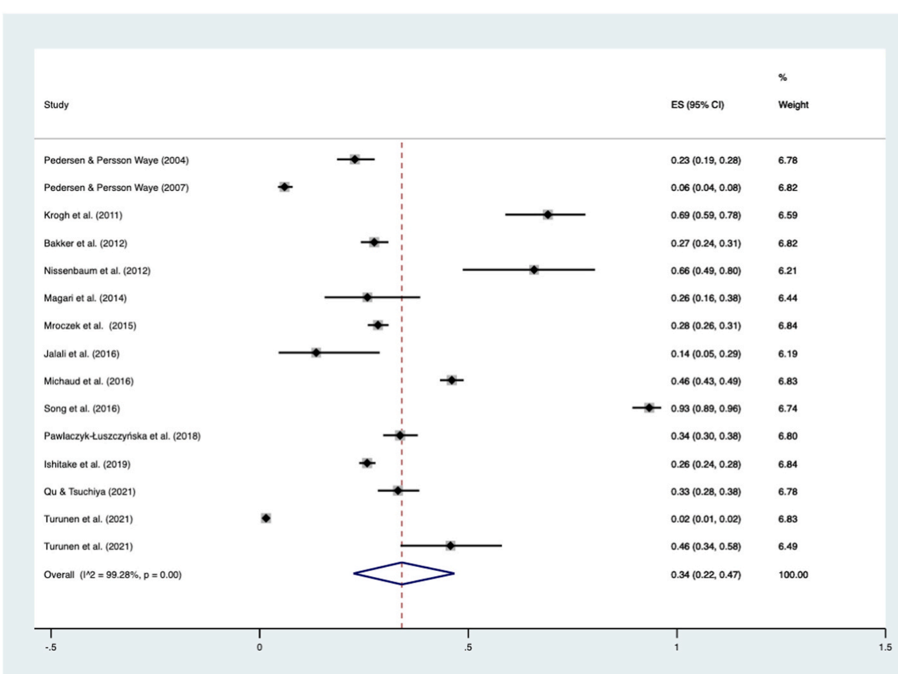

Fig. 2. Meta-analysis of the prevalence of sleep disorders in residents living near wind turbines. (ES: Effect Size, CI: Confidence Interval).

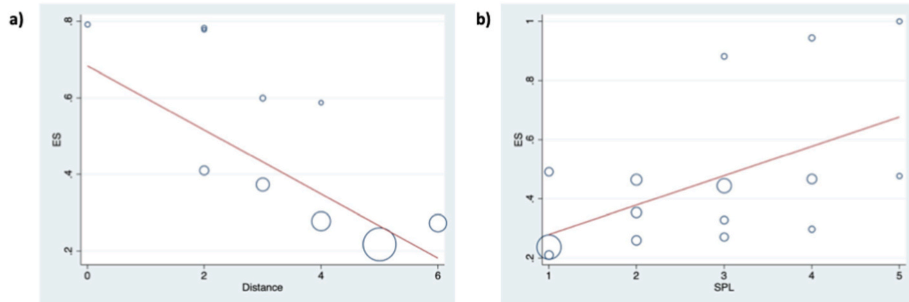

Fig. 3. Univariate meta-regression of the prevalence of sleep disorders by a) distance (p = 0.010) and b) sound power level (SPL) according to the following categories (1=<30 dB, 2 = 30–35 dB, 3 = 35–40 dB, 4 = 40–45 dB, 5= >45 dB (p = 0.037). Individual studies are represented by circles, with the size of the circle being inversely proportional to the variance of the estimated treatment effect (i.e. the larger the circle, the more precise the estimated treatment effect). The dotted line represents the regression line for the analysis.

sleep disorders that are difficult to compare. These confounders may have resulted in less reliable data from the original studies. Finally, sleep disorders are highly prevalent in the general population, with heterogeneous prevalence rates that vary between countries. For this reason, and due to the methodological limitations of the general population-based study mentioned above, it is difficult to understand the impact of WTs exposure on sleep disturbance. Consequently, we cannot state whether our value is higher or lower in absolute terms.

4.2. Sleep disorders due to transportation noise

WTs are responsible for producing a relatively large audible/sub-audible noise in low-frequency and infrasound spectra. Another source of low-frequency emissions is background noise from many environmental sources such as road traffic, railways, and aircraft. Several studies are in agreement on the association of exposure with worse sleep outcomes (European Environmental Agency, 2022; Perron et al., 2012; Smith et al., 2022). The World Health Organization (WHO) recently published the Environmental Noise Guidelines for the European Region (Clark and Paunovic, 2018), highlighting knowledge gaps and research needs on this matter. They found limited evidence on the health impacts of transportation noise from large-scale cohort and case-control studies with objective measurements of both noise exposure and health outcomes. Moreover, it is difficult to establish whether the actual cause of sleep disturbances due to transportation noise is fully related to the low-frequency spectrum.

4.3. Relationship between sleep disorders and distance/SPL

As expected, in our study, the prevalence of sleep disorders decreased with increasing distance from WTs and decreasing SPL. Our results are similar to those reported by Onakpoya et al. (2015), where higher exposure to SPL revealed a significant increase in the chances of reporting sleep disturbances (OR 2.94; 95% Cl, 1.98–4.37). It should be highlighted that while the relationship between sleep disorders and SPL is based only on noise emissions, distance can be related to all WTs emissions, including visual impact. However, only four studies stratified sleep disorders by SPL and three by distance, increasing the risk of overfitting, thus reducing the generalizability of our conclusions.

4.4. Sleep disorders and objective measures of sleep quality

A systematic review and meta-analysis conducted by Liebich et al. (2020) focused on the impact of exposure to WTs using objective measures of sleep assessment, such as polysomnography and actigraphy. Their results showed no significant differences in objective sleep onset latency (0.03; 95% CI, -0.34–0.41), total sleep time (−0.05; 95% CI, -0.77–0.67), sleep efficiency (−0.25; 95% CI, -0.71–0.22), or wake-up after sleep onset (1.25; 95% CI, -2.00–4.50) in the presence versus absence of WTs (all p > 0.05). The authors did not stratify health outcomes and WTs exposure according to the SPL or distance.

4.5. Sleep disorders and experimental studies

Other studies have used experimental approaches to verify the hypothesis that WT noise is responsible for sleep-related health effects. However, it is difficult to simulate real-life conditions, such as exposure to WT noise, and consider the dose and duration of exposure. Moreover, experimental studies did not consider other sources of emissions. Finally, experimental studies cannot consider other factors related to WT-related annoyance, such as visual landscape impact, visual annoyance caused by stroke effects, moving shadows, safety issues, or social aspects (Simos et al., 2019). Experimental studies typically benefit from both controlled and replicable exposure conditions. For instance, Dunbar et al. (2021) examined the effect of WT noise compared with road traffic noise on sleep using quantitative electroencephalogram (EEG) power spectral analysis. Twenty-three participants were exposed to 3-min samples of WT noise and road traffic noise at three sound pressure levels (33, 38, and 43 dBA) in random order during established sleep. Their spectral analysis results showed subtle effects of noise on sleep, and that EEG changes after WT noise and road traffic noise onset differed depending on the SPLs. However, all the reported effects were mostly transient and had little impact on sleep scores. A study by Kasprak et al. (Kasprzak, 2014) investigated EEG variations in the delta, theta, alpha, SMR, Beta1, and Beta2 waves in humans exposed to infrasound noise. The experiment consisted of playing acoustic signals recorded from the WT at 750 m while testing EEG electric signals from 35 subjects. Their results showed changes in the EEG signal patterns registered under exposure to WT noise, and the specific frequency ranges of the EEG signals were altered.

4.6. Sleep disorders and factors not related to noise exposure

Another set of studies (Crichton et al., 2014a, 2014b; Crichton and Petrie, 2015) hypothesized that other factors, in addition to noise exposure, may contribute to the occurrence of health disorders and sleep disorders related to WT exposure. Some studies indicate that perceived symptoms can be explained by the nocebo response, whereby health concerns and negative expectations created from social discourse and media reports could trigger the reporting of symptoms. Other studies have suggested that negative expectations through WTs can create symptoms, or that positive expectations can produce the opposite effect, in terms of a reduction in symptoms and improvements in reported health. Moreover, several studies included in our review emphasized that sleep disturbance was highly correlated to subjective annoyance.

4.7. Limitations

This systematic review and meta-analysis has some limitations. The design of the included studies was cross-sectional and therefore could not be used to determine any specific causal relationships. The outcome was frequently measured using a single-question with various ranges of response scales and different reference timeframes for sleep disorders, making it difficult to compare the results of the included studies.

There was substantial heterogeneity in the definition of sleep disorders, and the response rates were often less than 50%, with an increased risk of selection bias. The quality of the included studies varied significantly. However, the overall level of evidence for the included studies was considered poor, with some of the elements considered in the quality assessment tool generally receiving low scores. Only a few studies have provided justifications for the sample size or discussed the statistical power of the study. Furthermore, less than half of the included studies stratified the prevalence results according to distance or SPL. Moreover, SPL measurements slightly differed between studies.

Experimental and laboratory studies were excluded because there were few reports with modalities of execution and experimental conditions that were very dissimilar or hardly comparable. Moreover, experimental and laboratory studies have been conducted on highly selected populations, making the results difficult to generalize. Observational studies are conducted in real-life contexts that are crucial for epidemiology as they allow researchers to test their assumptions and provide reliable evidence for making decisions in real-life population health interventions.

Additionally, self-reports can suffer from recall bias, particularly when the questions relate to the previous 12 months, as is typical for questions about sleep disturbance in most of the studies included in our meta-analysis. The results were not adjusted for all plausible confounders such as annoyance and other environmental stressors, including air pollution, light, temperature, and humidity. Furthermore, it is not possible to determine whether the association between exposure to WTs and sleep disorders is only caused by exposure to noise or whether other aspects, such as visual disturbances, economic problems, or attitudes toward noise, can affect the prevalence of sleep disorders.

5. Conclusions

These findings suggest that there may be a dose-response relationship between exposure to WTs and sleep disorders, although no conclusions can be drawn for causality. Future research should better define the pathologies that should be considered under the umbrella term 'sleep disorders' to compare the results of different studies. Future large-scale studies should adopt a longitudinal design and focus on objective measurements for the evaluation of sleep disorders, supported by validated subjective methods, such as questionnaires. Experimental studies in the same population could also provide information on the mechanisms linking exposure to WTs and sleep disorders.

Author contribution

Conceptualization, BD, NN, PB; Methodology, AG, MC, PB; Literature search and data abstraction: IM, GC, AF, ECa, VDP; Statistical analysis, AG, MC, CC; Writing – Original Draft Preparation, AG, MC, CC; Writing – Review & Editing, EP, BD, NN, PB; Supervision, AG, EP, PB; Project Administration, PB; Funding Acquisition, BD, NN, PB.

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Declaration of competing interest

Paolo Boffetta, Bruno Dallapiccola and Nicola Normanno received a honorarium as members of the scientific committee of Fondazione Eni Enrico Mattei (FEEM). Other Authors declare no conflict of interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2023.114273.

References

Bakker, R.H., Pedersen, E., Berg, G.P. Van Den, Stewart, R.E., Lok, W., Bouma, J., 2012. Impact of wind turbine sound on annoyance , self-reported sleep disturbance and psychological distress. Sci. Total Environ. 425, 42–51. https://doi.org/10.1016/j.scitotenv.2012.03.005.

Barendregt, J.J., Doi, S.A., Lee, Y.Y., Norman, R.E., Vos, T., 2013. Meta-analysis of prevalence. J. Epidemiol. Community Health 67, 974–978. https://doi.org/10.1136/jech-2013-203104, 1978.

Bodini, N., Lundquist, J.K., Moriarty, P., 2021. Wind plants can impact long-term local atmospheric conditions. Sci. Rep. 11 https://doi.org/10.1038/s41598-021-02089-2.

Clark, C., Paunovic, K., 2018. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and quality of life, wellbeing and mental health. Int. J. Environ. Res. Publ. Health 15. https://doi.org/10.3390/ijerph15112400.

Crichton, F., Dodd, G., Schmid, G., Gamble, G., Cundy, T., Petrie, K.J., 2014a. The power of positive and negative expectations to influence reported symptoms and mood during exposure to wind farm sound. Health Psychol. 33, 1588–1592. https://doi.org/10.1037/hea0000037.

Crichton, F., Dodd, G., Schmid, G., Gamble, G., Petrie, K.J., 2014b. Can expectations produce symptoms from infrasound associated with wind turbines? Health Psychol. 33, 360–364. https://doi.org/10.1037/a0031760.

Crichton, F., Petrie, K.J., 2015. Health complaints and wind turbines: the efficacy of explaining the nocebo response to reduce symptom reporting. Environ. Res. 140, 449–455. https://doi.org/10.1016/j.envres.2015.04.016.

Dunbar, C., Catcheside, P., Lechat, B., Hansen, K., Zajamsek, B., Liebich, T., Phuc, D., Hannah, N., Lack, L., Decup, F., Vakulin, A., Micic, G., 2021. RESEARCH ARTICLE EEG power spectral responses to wind farm compared with road traffic noise during sleep. A laboratory study 1–11. https://doi.org/10.1111/jsr.13517.

Egger, M., Smith, G.D., Schneider, M., Minder, C., 1997. Bias in meta-analysis detected by a simple, graphical test. BMJ 315, 629–634. https://doi.org/10.1136/bmj.315.7109.629.

European Environmental Agency, 2022. Health Impacts of Exposure to Noise from Transport [WWW Document].

GWEC, 2022. Global Wind Report-2022 n.d.

Ishitake, T., Morimatsu, Y., Hara, K., 2019. Epidemiological Study on Long-Term Health Effects of Low-Frequency Noise Produced by Wind Power Stations in Japan 1455–1462.

Jahrami, H., BaHammam, A.S., Bragazzi, N.L., Saif, Z., Faris, M., Vitiello, M. v, 2021. Sleep problems during the COVID-19 pandemic by population: a systematic review and meta-analysis. J. Clin. Sleep Med. 17, 299–313. https://doi.org/10.5664/jcsm.8930.

Jalali, L., Nezhad-Ahmadi, M.R., Gohari, M., Bigelow, P., McColl, S., 2016. The impact of psychological factors on self-reported sleep disturbance among people living in the vicinity of wind turbines. Environ. Res. 148, 401–410. https://doi.org/10.1016/j.envres.2016.04.020.

Karna, B., Sankari, A., Tatikonda, G., 2022. Sleep Disorder.

Kasprzak, C., 2014. The influence of infrasound noise from wind turbines on EEG signal patterns in humans. Acta Phys. Pol. 125, 20–23. https://doi.org/10.12693/APhysPolA.125.A-20.

Katzner, T.E., Nelson, D.M., Braham, M.A., Doyle, J.M., Fernandez, N.B., Duerr, A.E., Bloom, P.H., Fitzpatrick, M.C., Miller, T.A., Culver, R.C.E., Braswell, L., DeWoody, J. A., 2017. Golden Eagle fatalities and the continental-scale consequences of local wind-energy generation. Conserv. Biol. 31, 406–415. https://doi.org/10.1111/cobi.12836.

Krogh, C.M.E., Gillis, L., Kouwen, N., Aramini, J., 2011. WindVOiCe , a self-reporting survey : adverse health effects , industrial wind turbines , and the need for vigilance monitoring. https://doi.org/10.1177/0270467611412551.

Lane, J.D., Bigelow, P.L., Majowicz, S.E., McColl, R.S., 2016. Impacts of industrial wind turbine noise on sleep quality: results from a field study of rural residents in ontario, Canada. J. Environ. Health 79, 8–12.

Léger, D., Poursain, B., Neubauer, D., Uchiyama, M., 2008. An international survey of sleeping problems in the general population. Curr. Med. Res. Opin. 24, 307–317. https://doi.org/10.1185/030079907x253771.

Li, C., Mogollón, J.M., Tukker, A., Steubing, B., 2022. Environmental impacts of global offshore wind energy development until 2040. Environ. Sci. Technol. 56, 11567–11577. https://doi.org/10.1021/acs.est.2c02183.

Liebich, T., Lack, L., Hansen, K., Zajamšek, B., Lovato, N., Catcheside, P., Micic, G., 2020. A systematic review and meta-analysis of wind turbine noise effects on sleep using validated objective and subjective sleep assessments 1–23. https://doi.org/10.1111/jsr.13228.

Magari, S.R., Smith, C.E., Schiff, M., Rohr, A.C., 2014. Evaluation of community response to wind turbine-related noise in Western. New York State 16, 228–239. https://doi.org/10.4103/1463-1741.137060.

Michaud, D.S., Feder, K., Keith, S.E., Voicescu, S.A., Marro, L., Than, J., Guay, M., Denning, A., Murray, B.J., Weiss, S.K., Villeneuve, P.J., van den Berg, F., Bower, T., 2016. Effects of wind turbine noise on self-reported and objective measures of sleep. Sleep 39, 97–109. https://doi.org/10.5665/sleep.5326.

Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L.A., 2015. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst. Rev. 4, 1. https://doi.org/10.1186/2046-4053-4-1.

Mroczek, B., Banaś, J., Machowska-Szewczyk, M., Kurpas, D., 2015. Evaluation of quality of life of those living near a wind farm. Int. J. Environ. Res. Publ. Health 12, 6066–6083. https://doi.org/10.3390/ijerph120606066.

NIH, 2014. Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies [WWW Document]. URL. https://www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools. accessed 6.26.23.

Nissenbaum, M.A., Aramini, J.J., Hanning, C.D., 2012. Effects of industrial wind turbine noise on sleep and health. Noise Health 14, 237–243. https://doi.org/10.4103/1463-1741.102961.

Nyaga, V.N., Arbyn, M., Aerts, M., 2014. Metaprop: a Stata command to perform meta-analysis of binomial data. Arch. Publ. Health 72, 39. https://doi.org/10.1186/2049-3258-72-39.

Onakpoya, I.J., O'Sullivan, J., Thompson, M.J., Heneghan, C.J., 2015. The effect of wind turbine noise on sleep and quality of life: a systematic review and meta-analysis of observational studies. Environ. Int. 82, 1–9. https://doi.org/10.1016/j.envint.2015.04.014.

Pawlaczyk-Łuszczyńska, M., Zaborowski, K., Dudarewicz, A., Zamojska-Daniszewska, M., Waszkowska, M., 2018. Response to noise emitted by wind farms in people living in nearby areas. Int. J. Environ. Res. Publ. Health 15. https://doi.org/10.3390/ijerph15081575.

Pedersen, E., Persson Waye, K., 2004. Perception and annoyance due to wind turbine noise—a dose–response relationship. J. Acoust. Soc. Am. 116, 3460–3470. https://doi.org/10.1121/1.1815091.

Pedersen, E., Waye, K.P., 2007. Wind turbine noise, annoyance and self-reported health and well-being in different living environments. Occup. Environ. Med. 64, 480–486. https://doi.org/10.1136/oem.2006.031039.

Perron, S., Tétreault, L.-F., King, N., Plante, C., Smargiassi, A., 2012. Review of the effect of aircraft noise on sleep disturbance in adults. Noise Health 14, 58–67. https://doi.org/10.4103/1463-1741.95133.

Pierpont, N., 2009. Wind Turbine Syndrome: A Report on a Natural Experiment.

Qu, F., Tsuchiya, A., 2021. Perceptions of wind turbine noise and self-reported health in suburban residential areas. Front. Psychol. 12, 1–12. https://doi.org/10.3389/fpsyg.2021.736231.

REN21, 2021. Renewables 2021 Global Status Report.

Simos, J., Cantoreggi, N., Christie, D., Forbat, J., 2019. Wind turbines and health: a review with suggested recommendations. Environnement, Risques & Santé 18, 149–159. https://doi.org/10.1684/ers.2019.1281.

Smith, M.G., Cordoza, M., Basner, M., 2022. Environmental noise and effects on sleep: an update to the WHO systematic review and meta-analysis. Environ. Health Perspect. 130, 76001 https://doi.org/10.1289/EHP10197.

Smith, M.G., Ögren, M., Thorsson, P., Hussain-Alkhateeb, L., Pedersen, E., Forssén, J., Ageborg Morsing, J., Persson Waye, K., 2020. A laboratory study on the effects of wind turbine noise on sleep: results of the polysomnographic WiTNES study. Sleep 43. https://doi.org/10.1093/sleep/zsaa046.

Solarin, S.A., Bello, M.O., 2022. Wind energy and sustainable electricity generation: evidence from Germany. Environ. Dev. Sustain. 24, 9185–9198. https://doi.org/10.1007/s10668-021-01818-x.

Song, K., Di, G., Xu, Y., Chen, X., 2016. Community survey on noise impacts induced by 2MW wind turbines in China. J. Low Freq. Noise Vib. Act. Control 35, 279–290. https://doi.org/10.1177/0263092316676399.

Stefko, R., Gavurova, B., Kelemen, M., Rigelsky, M., Ivankova, V., 2021. Relationships between renewable energy and the prevalence of morbidity in the countries of the European union: a panel regression approach. Int. J. Environ. Res. Publ. Health 18. https://doi.org/10.3390/ijerph18126548.

Turunen, Anu W., Tiittanen, P., Yli-Tuomi, T., Taimisto, P., Lanki, T., 2021. Symptoms intuitively associated with wind turbine infrasound. Environ. Res. 192, 110360 https://doi.org/10.1016/j.envres.2020.110360.

Turunen, Anu W., Tiittanen, P., Yli-Tuomi, T., Taimisto, P., Lanki, T., 2021a. Self-reported health in the vicinity of five wind power production areas in Finland. Environ. Int. 151, 106419 https://doi.org/10.1016/j.envint.2021.106419.

Turunen, Anu W., Tiittanen, P., Yli-Tuomi, T., Taimisto, P., Lanki, T., 2021b. Symptoms intuitively associated with wind turbine infrasound. Environ. Res. 192, 110360 https://doi.org/10.1016/j.envres.2020.110360.