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Effect of Wind Turbine Noise on Workers' Sleep Disorder: A Case Study of ManjilWind Farm in Northern Iran

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Noise from wind turbines is one of the most important factors affecting the health, welfare, and human sleep. This research was carried out to study the effect of wind turbine noise on workers' sleep disorder. For this, Manjil Wind Farm, because of the greater number of staff and turbines than other wind farms in Iran, was chosen as case study. A total number of 53 participants took part in this survey. They were classified into three groups of mechanics, security, and official. In this study, daytime sleepiness data of workers were gathered using Epworth Sleepiness Scales (ESS) was used to determine the level of daytime sleepiness among the workers. The 8-h equivalent sound level (LAeq,8h) was measured to determine the individuals' exposure at each occupational group. Finally, the effect of sound, age, and workers' experience on individuals' sleep disorder was analyzed through multiple regression analysis in the R software. The results showed that there was a positive and significant relationship between age, workers' experience, equivalent sound level, and the level of sleep disorder. When age is constant, sleep disorder will increase by 26% as per each 1 dB increase in equivalent sound level. In situations where equivalent sound level is constant, an increase of 17% in sleep disorder is occurred as per each year of work experience. Because of the difference in sound exposure in different occupational groups. The effect of noise in repairing group was

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about 6.5 times of official group and also 3.4 times of the security group. Sleep disorder effect caused by wind turbine noise in the security group is almost two times more than the official group. Unlike most studies on wind turbine noise that address the sleep disorder among inhabitants nearby wind farms, this study, for the first time in the world, examines the impact of wind turbine noise on sleep disorder of workers who are more closer to wind turbines and exposed to higher levels of noise. So despite all the good benefits of wind turbines, it can be stated that this technology has health risks for all those exposed to its sound. However, further research is needed to confirm the results of this study.

Keywords: Wind turbine noise; low frequency noise; sleep disorder; wind farm; workers.

1. Introduction

Wind energy is a new form of electric power generation, which has fewer effects on the environment compared to other sources of energy [1]. In recent decades, the use of wind energy has become more common and in consequent, large number of wind farms and turbines are being built. This has enhanced public awareness about the effects of wind energy on human health and environment and many studies have been done in this area [2, 3]. The wind turbine noise is one of obstacles preventing the wide spread use of wind energy [4]. It can be divided as aerodynamic noise and mechanical noise. Aerodynamic noise is related to the low frequency sound of wind turbines, generated from the flow of air over the turbine blades. when Mechanical noise can be caused by different parts of wind turbine such as gearbox, generators, etc. [5, 6]. Leventhall in 2006 declared that this type of sound is composed of a partly low frequency sound and a little infrasound [7]. Wind turbine can generate amplitude modulations, low frequency audible sound, tonal noise, impulse noise, and night time noise [7–9], each with possible harmful effects.

Roger in 2006 attributed the harmful effect of wind turbine noise to the low frequency sound and infrasound [10]. Generally, the noise impacts can be classified as:

(1) Mental effects such as: Annoyance, nausea, and un-satisfaction.
(2) Disorders in learning, speaking, and sleeping.
(3) Physiological effects such as anxiety, tinnitus, and hearing loss [10].

However, Pederson in 2007 suggested that the side effects are just limited to the first two groups [11].

Low frequency sound and infrasound have important impacts on human health. Many studies have been done in this area and the results are compatible with the reality of unwanted health problems reported. Much research has argued that there is no sufficient evidence to confirm the detrimental effects of low frequency sound and infrasound caused by turbine noise [12–17]. However, symptoms of complications such as annoyance, sleep disorders, stress, and decreased quality of life have been reported among people who live nearby wind turbines [18, 2]. According to Chouard in 2006, people in the vicinity of industrial wind turbines have experienced problems such as headache, tiredness, temporary vertigo, nausea, insomnia, and heartbeat [19].

Griefahn in 1991 defined sleep disorder as a measurable variance from a normal or desirable sleep, which is accompanied by symptoms before and after sleep [20]. The adverse effect of wind turbine noise on sleep disorder has been reported by many researchers worldwide. As such, Leventhall in 2003 investigated that low frequency sound such as wind turbine noise may have serious effects on individuals' health and cause sleep disorder [21]. In a study by Hestro in 2004, it was revealed low frequency sound of air conditioner systems in residential areas can cause sleep disorder [22]. Sleep disorder often leads to feeling *tired and groggy the next day* [23]. Nissenbaum in 2012 argued that people who live nearby wind turbines have experienced levels of sleep disorder [18]. WHO knows sleep disorder as one of the main effects of noise on human health [24]. In 2013, researchers showed there was a significant relationship between sleep disorder and the distance of inhabitants from the wind turbines [25]. All previous surveys on the sleep disorder caused by wind turbine noise have been done on people nearby wind farms. In other studies, the sound effects on staff sleep disturbance were considered and the nature of the studied sound was different from wind turbine sound.

The important point is that workers at wind farms are the closest people to this noise source and exposed to higher noise levels than the surrounding inhabitants. Thus, the detrimental effects on the workers' health are expected to be much higher. Therefore, this study was done in order to investigate the impact of wind turbine noise on sleep disorder of workers who are exposed to the harmful effects of low frequency sound of turbines.

2. Material and Methods

2.1. *Study area*

In this research, Manjil Wind Farm, was chosen as the study because of its greater number of staff and turbines than other wind farms inIran. Manjil wind farm is the largest wind farm in Iranwhich launched in two decades ago in a windy area in the north of Iran and in a suburb of Manjil Turbines installed in this plant have been horizontal-axis turbines that the installation height Reaches to 45 m and installed at different distances from each other and they have different power electricity generation (300, 500, 550, 600 and 660 KW).

2.2. *Subjects*

Participants in this survey were the personnel of Manjil Wind Farm. Sampling was done by taking census. Based on responsibility and workplace of the personnel, they were classified into three groups of repairing, security, and official. The repairing group is responsible for maintenance, and repairing of turbines, so they are very close to the turbines during much of their working shift hours. In some cases, in order to repair the turbine trunk at height, the relevant technician should be pretty close to this noise source. People in security group are in charge of guarding and controlling of the entrance and exit gates and they stand guard at the stations, alternatively. The security group has a further distance from the turbines compared to the repairing group. The workers at this group have a variable shift with a fixed workplace. Official personnel work in an 8-h shift as same as the repairing group. They are in charge of office affairs. Official personnel has the farthest distance from the turbines compared to the other groups.

2.3. *Sound measurement*

The exposure level of workers at each work group to wind turbine noise was measured using eight-hour equivalent sound level (LAeq,8h) according to ISO 9612:2009 [26]. For generalizing the results of exposure in various occupations, similarity of operations were considered. In some places where workers spend most of their time, sound frequency was analyzed in octave band by a sound meter, *TES-1358 Sound Analyzer*.

2.4. *Questionnaires*

A questionnaire was prepared to collect demographic data and workers' background information such as age, work experience, work shift, level of education, etc. moreover, the ESS questionnaire was used to determine individuals' sleep disorder and their daily drowsiness. Some exploratory meetings were held with workers on how to fill out the questionnaires. The questionnaires were filled out by the volunteer workers and send them back for final evaluation.

2.5. *Epworth sleepiness scale*

The ESS questionnaire was designed in 1991 by Murray Johns of Epworth Hospital in Melbourne, Australia. It offers a scale to measure daytime sleepiness. This questionnaire contains eight questions that mark drowsiness of subjects on a scale of increasing probability from 0 to 3 for eight different situations. The final score varies 0 and 24. A number in the range of 10–24 is recognized abnormal (high sleepiness). The ESS has a global reliability and validity estimated by Cronbach's alpha in the range of 73% to 88% [27].

2.6. *Statistical analysis*

In this research, the questionnaires were analyzed by R software. Further, the correlation among variables was checked using Spearman and Pearson correlation tests. Multiple regression analysis was used to determine relationship between wind turbine noise and sleep disorder among the workers at Manjil Wind Farm. The means of sleep disorder among the various groups were compared through One Way ANOVA and Kruskal–Wallis.

3. Results

A total number of 53 employees of Manjil Wind Farm participated in this survey that was conducted in 2014. The mean age of an of the participants was 30.8 years and their average work experience was 14 years.

The values of LAeq,8h among repairing, security, and official groups were equal to 83,66 dB (A) and 60 dB (A), respectively.

The results of frequency analysis showed that sound pressure level in all central frequencies of octave band was higher among repairing group in comparison with the security and official parts. Moreover, the sound pressure balance was higher at low frequencies. The more frequency increases, the more sound pressure balance decreases. The obtained results are shown in Table 1.

The average sleep disorder among the participant was measured equal to 7.3. The average daytime sleepiness among repairing group members and those workers with more than 19 years of work experience were 10.5 and 10.1, respectively. This reveals the abnormal *sleep* pattern of the workers feeling *abnormally sleepy* during

Table 1. Sound frequency analysis results in different job groups.

Frequency job groups	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Repair	88	87	87	86	85	78	69	65	59
Security	74	73	65	60	59	52	48	45	43
Official	63	61	60	54	54	50	46	41	34

Table 2. Sleep disorder results in terms of job groups, work experience, level of education, and shift work.

Overall sleep disorder		Mean	Median	Mode	SD	Max	Min
		7.3	7	4	3.1	15	2
Disord							
Job	Repair	10.5	10	9	1.7	15	8
	Security	6	7	7	1.4	8	3
	Official Staff	4	4	4	0.91	5	2
Age	. . . <36	6	5	4	2.4	10	2
	36–41	7.5	7	10	3	13	3
	41< . . .	10.2	11	7	3.2	15	5
Experience	. . . <12	5.6	5	4	2.4	10	2
	12–19	7.4	7	7	2.8	13	3
	19< . . .	10.1	11	11	3	15	5
Level of education	. . . <diploma	7.2	6	4	3.9	15	3
	diploma≤ . . .	7.4	7	7	2.9	13	2
Work shift	Fixed	7.9	9	4	3.4	15	2
	circular	6	7	7	1.5	8	3

the day. Sleep disorder results are presented in Table 2 in separation of job groups, work experience, level of education, and shift type.

Pearson correlation confirms a significant relationship between workers' sleep disorder and the equivalent sound level at a confidence level of 5%. The correlation coefficient was equal to 87%. Then, the effect of sound equivalent level on the workers' sleep disorder was studied by the simple linear regression. According to the results, every 1 dB increase in sound equivalent level will lead to an increase of 28% in sleep disorder among the workers.

As mentioned earlier, the distribution of sleep disorder among the three groups was investigated by Kruskal–Wallis test. The obtained results indicated that sleep disorder among the three exposed groups is not equal and there is statistically a significant difference among the population means at a confidence level of 95% (Fig. 1).

Dummy coding was used to study the effect of noise exposure on sleep disorder. The official personnel with a minimum possible sleep disorder were selected as the control group. The outcomes showed that occupation type can justify 78% of changes in response variable which is sleep disturbance alone. The wind turbine exposure has the greatest effect on the individual's sleep disorder in repairing group at a confidence level of 95%. The noise effect in repairing group was about 6.5 times of official group and also 3.4 times of the security group. Sleep disorder effect caused

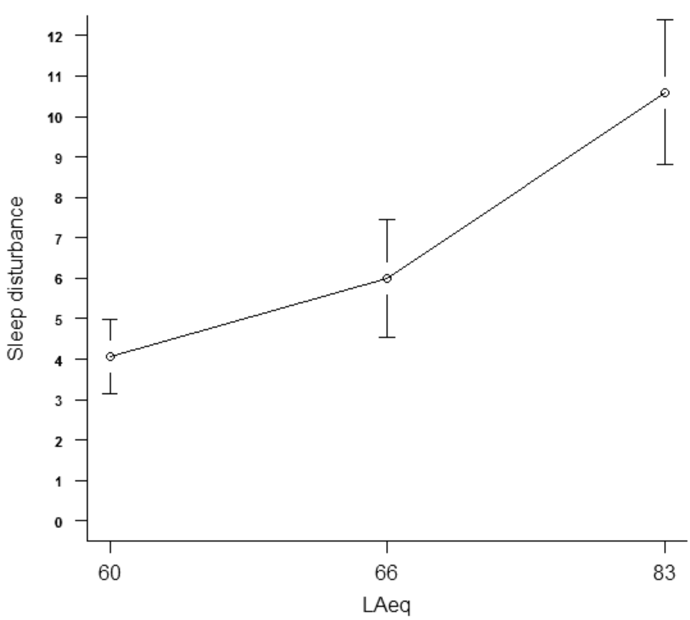

Fig. 1. Distribution of sleep disorder at different levels of LAeq.

Table 3. Effect of noise exposure on sleep disorder among different job groups.

	Model consistent		Model coefficient						
	F	p-Value	Regression coefficient (B)	Std. error	Beta	T	p-Value	R	R square
Control	91.85	0.00	4.07	0.4	—	10.16	0.00	0.88	0.78
Security			1.92	0.54	0.28	3.52	0.00		
Repairing			6.51	0/51	1.02	12.72	0.00		

by wind turbine noise in the security group is almost two times more than the official group (Table 3).

Relationship between workers' age and sleep disorder was detected using Pearson correlation analysis. There was found a significant correlation between workers' sleep disorder and their age at a confidence level of 95%. The correlation level was reported 50%.

Then, the age effect on workers' sleep disorder was studied by the simple linear regression. The obtained results showed that the workers' sleep disorder will increase by 0.26 for every year increase inage. The linear relationship between age and sleep disorder is depicted in Fig. 2.

The one way ANOVA test was used to compare average sleep disorder difference in different age groups. The obtained results showed that the sleep disorder average is not equal in different age groups were not equal. The variance was statistically significant at a confidence level of 95% (p-value < 0.05) (Fig. 3).

Relationship between sleep disorder and work experience was studied by Pearson correlation analysis at a confidence level of 95%. The results showed that sleep disorder correlates significantly with work experience. The correlation level is 50%.

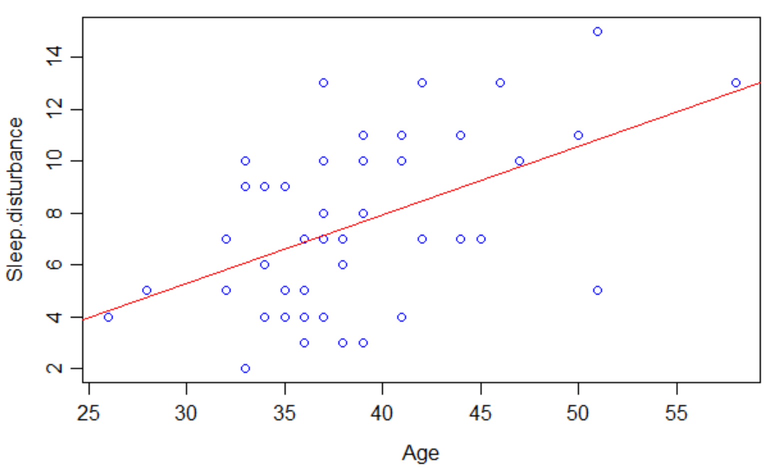

Fig. 2. Linear relationship between age and sleep disorder.

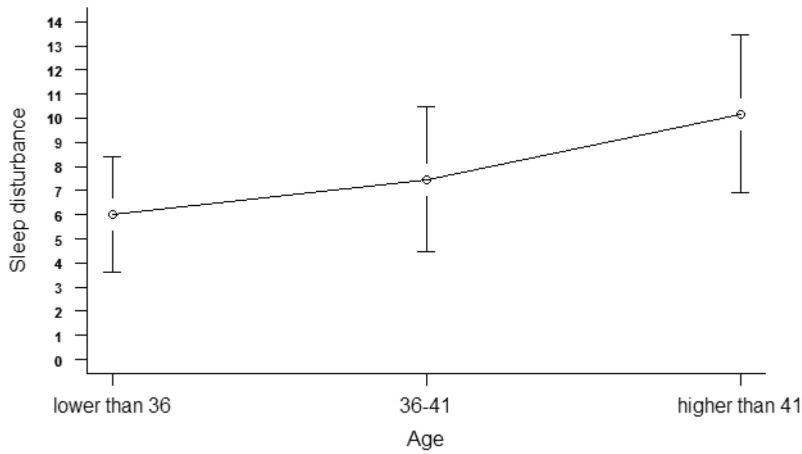

Fig. 3. Comparison of average sleep disorder values among different age groups.

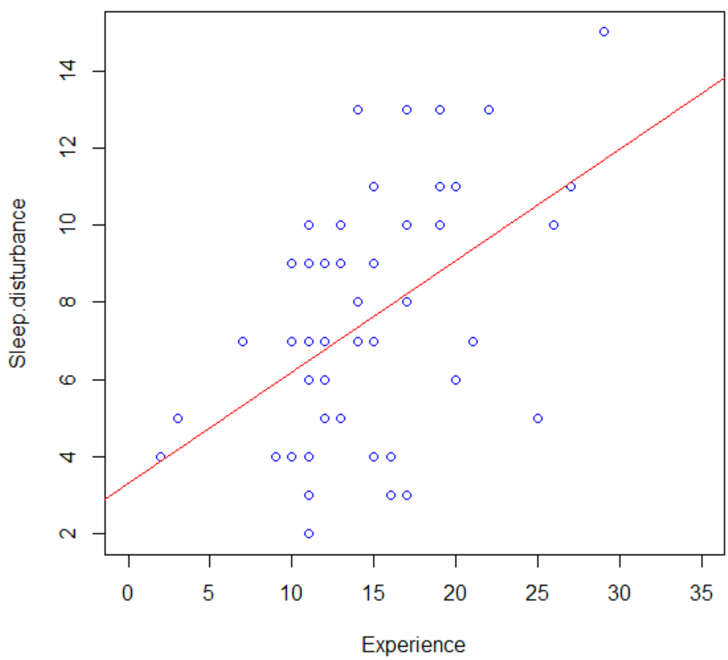

Fig. 4. Relationship between work experience and sleep disorder.

Then, the effect of work experience on sleep disorder was studied by the simple linear regression. According to the results, for every year of work experience, level of sleep disorder rises by 29%. The linear relationship between work experience and sleep disorder is illustrated in Fig. 4.

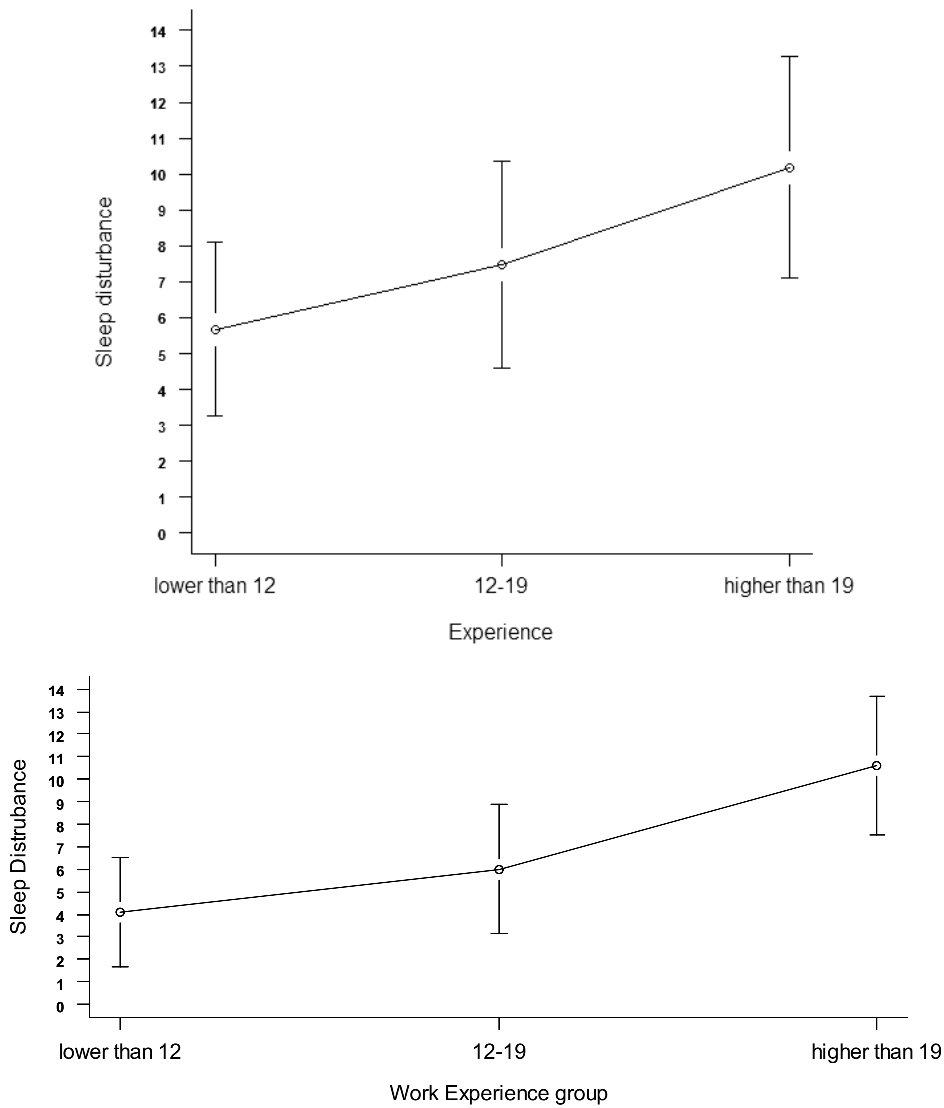

Fig. 5. Comparison of sleep disorder among workers with different work experience.

The ANOVA test was used to compare the average of sleep disorder among different groups with different work experience. The outcomes showed that difference in average sleep disorder among different groups is statistically significant at a confidence level of 95% (p-value < 0.05) (Fig. 5).

The effects of three variables including age, work experience, and equivalent sound level on workers' sleep disorder was investigated by multiple regression test. The results confirmed the fact that when age is constant, sleep disorder will increase

Table 4. Effect of age, work experience, and LAeq on sleep disorder.

	Model consistent		Model Coefficients						
	F	p-Value	Regression coefficient (B)	Std. error	Beta	T	p-Value	R	R square
constant	83.47	0.001	−16.72	2.06	—	−8.12	0.001	0.88	83.47
LAeq			0.26	0.02	0.82	13.05	0.001		
Age			0.17	0.06	0.31	2.27	0.001		
Experience			−0.05	0.07	−0.09	−0.8	0.42		

by 26% as per each 1 dB increase in equivalent sound level. In situations where equivalent sound level is constant, an increase of 17% in sleep disorder is occurred as per each year of work experience. Work experience, at the confidence level of 95%, has no significant effect on sleep disorder (Table 4).

4. Discussion

One of the major effects of environmental noise is sleep disorder [28]. The road and air traffic noise is one of the most important environmental risk factors increases the possibility of sleep disorder. This has been always been a matter of concern for researchers worldwide [29, 30]. Recently, wind turbine noise has been discussed as an effective factor on sleep quality of inhabitants nearby wind farms [31]. However, there is no study done on workers' sleep disorder at wind farms. Accordingly, the present research was performed to investigate the effects of wind turbine noise on sleep quality of workers in Manjil Wind Farm, northern Iran.

The obtained results indicated that sleep disorder increases as the equivalent sound level increases. According to which, the average sleep disorder in repairing group who were exposed to a higher level of turbine noise were 1.75 times the security group and 2.62 times and the official staff. Kruskal–Wallis test shows a significant difference between average sleep disorder among the occupational groups (p-value < 0.05). The results from the simple linear regression model revealed that the equivalent sound level accounts for 78% of sleep problems. The effect of the equivalent sound level on the repairing group is higher than that of security and official groups. The sleep disorder in repairing group is about 6.5 times the official staff and 3.4 times the security group. American Academy of Sleep Medicine has introduced sleep disorder as a bothering factor, which results in many complains on insomnia and daily drowsiness [32]. Kim *et al.* studied the effects of airplane noise on sleep quality of inhabitant near an army airport in Korea. They divided the exposed people into three groups of low sound exposure, high sound exposure, and control. Sleep disorder was 45.5% in control group, 71% in low exposure group, and 77.1% in high sound exposure group. They found a dose-response relationship between the airplane sound level and sleep quality [30]. Aside from the obvious differences in methods, tools, and materials used, the results of Kimand the present study both confirmed the dose-response relationship between exposure to equivalent sound level and sleep disorder. In the research by Kim and his colleagues, control group was located farther from the noise source. Therefore, they were less-exposed to noise and in consequent, fewer symptoms of sleep disorder were reported among them. Their findings can verify the results of the current study on the official group who experienced less exposure compared with security and repairing groups. In another research on inhabitants nearby wind turbines, a significant relationship was found between the distance from turbines and sleep disorder [25].

Öhrström *et al.* [22] investigated the effects on sleep of different types of noise exposures (road traffic, ventilation, and combination of noise from road traffic and ventilation) on sleep disorder in laboratory and in field settings. In the laboratory, judged sleep quality was decreased by 22% during nights with exposure to road traffic noise in the laboratory compared to the quiet reference night. In the lab environment, the sleep quality of individuals exposed to traffic and ventilation noise decreased respectively by 22% and 12% compared to the quiet reference night. The combined noise from ventilation and road traffic caused worse sleep quality of −25%. They could found no differences on sleep effects when comparing sleep with traffic noise exposure in the laboratory and in the home [22]. According to Öhrström *et al.* [22], it can be concluded that different sound levels with a variety of frequency spectrum can cause different levels of sleep disorder and the role of sound frequency and characteristics is very important in poor *quality of sleep* and awakening. Bruck *et al.* showed that low frequency sounds were more effective for awakening people from deep sleep [33]. This was confirmed by Solet *et al.* [34]. They emphasized said that impulsive sound caused more sleep disorder than other types of sound [34]. The noise from ventilation systems such as wind turbines are of low frequency type, which could adversely affect sleep quality. This it was confirmed by Öhrström *et al.* [22]. It can be claimed that turbine noise which is of low frequency and impulsive type may cause the same effect on sleep quality. This has been confirmed by Öhrström *et al.* and many others [22, 25, 28–30].

The Pearson test results showed that there is a significant and positive relationship between sleep disorder and workers' age. The correlation level is 50% (p-value < 0.05). Further, the results of ANOVA test indicated that the sleep disorder average is not equal among the different occupational groups (p-value < 0.05). Sleep disorder in those aged over 41 years were more visible than others. As the linear regression results suggest, 1 year in age will increase sleep disorder by 0.26. Older people are more are more prone to sleep disorder than younger people. The reason is that they have lost their hearing ability to hear high frequency sounds. It causes lack of coverage effect of the background sound on the sound created by wind turbine [28]. Many studies stated that age can be considered as a predictor for sleep [35, 36].

The effect of age on poorer sleep quality has been confirmed by Akerstedt *et al.* [37]. Dijk and Duffy in 1999 investigated age-related changes in the circadian and homeostatic regulation of human sleep they concluded that age-related changes may be related to changes in the sleep process itself, such as reductions in slow-wave sleep and sleep spindles as well as a reduced strength of the circadian signal promoting sleep in the early morning hours [38].

In this research, the combination effect of age, work experience, and equivalent sound level on sleep disorder was analyzed by multiple regression test. the results showed that age and sound exposure level totally account for 84% of sleeps Based on presented Regression coefficient in Table 4, it can be said that when sound equivalent Leveland age increase equally, the effect of sound equivalent Levelonsleep is more than the effect of age. Nissenbaum *et al.* [18] conducted a research to compare sleep and health outcomes of industrial wind turbines among participants living close to the turbines and those living further away from them. They found an exposure-response relationship between the distances from wind turbines and sleep disorder within the distance of 1.4 km from the industrial turbines [18].

The procedure, devices, and materials used by Nissenbaum *et al.* [18] was the same as the present study. However, the target groups of the two studies were different. As such, the present study addresses sleep disorder among wind farm workers while in the research by Nissenbaum *et al.* [39], inhabitants nearby the wind farms were selected as subjects. Higher level of sleep disturbance was reported in this study due to closer distance of the subjects to the noise source. wind turbine noise effect on repairing group was more visible than the security and official groups. This research and several other studies confirm different levels of dose-response relationship between the distance from wind turbines and sleep disorder as daily drowsiness [9, 25, 39]. The difference in dose-response relationship can be attributed to the different conditions (workers' characteristics, time and place of the study, wind speeds) in which the equivalent sound level was measured. Despite the close proximity of the staff to the wind turbine noise, the level of sleep disorder in workers of Manjil Wind Farm is less than that of reported by other studies on inhabitants nearby wind farms. This may be due to more knowledge, strength, and consistency of the workers compared to the ordinary people. Furthermore, workers may abstain from telling the truth of their sleep disorders due to the fear of punishment by their superiors and managers. However, working conditions and compatibility of personnel with the background noise are very important in disorders caused by wind turbine noise. Bakker *et al.* [31] investigated the impact of wind turbine noise on annoyance, self-reported sleep disturbance, and psychological distress.

No signs of sleep disorder was found among people who do not hear the turbine noise. They found a dose-response relationship between wind turbine noise and self reported noise annoyance. The outcomes showed that other environmental sounds such as the noise caused by traffic, animal, and human sounds may leave extra effects on sleep disturbance [31].

In this study, the visibility effects of turbines are known as an obtrusive factor in increasing the rate of sleep disorder among the workers in the repairing and security groups working outdoors. The official staff working in an enclosed workplace received less noise and experience less sleep disorder than the other two groups.

Previous studies confirm the annoyance effect of wind turbine noise on exposed individuals [2, 9, 40], which at last results in sleep disorder [31].

5. Conclusion

This study shows an exposure-response relationship between the wind turbine noise and workers' sleep disorder in Manjil Wind Farm rate. Based on this relationship, People who are working in close distance from turbines and have greater noise exposure, Experience more sleep disturbance. According to mentioned literature, sleep disorder caused by turbine noise is a great obstacle for development of wind farms. With this regards which the new wind turbines produce large amounts of low frequency sound Avoid these conditions, these conditions, which have high levels of low frequency sound for workers of wind power plant is not quite Avoidable But by applying the principles of engineering and administrative controls can improve worker sleep condition.

The positive point of our study was that we studied the effects of wind turbine and found a remedy for them practically. There were some constraints with the present study such as limited number of participants, ignoring of the interfere factors such as background sound level, individuals' characteristics (e.g., senility to noise, health conditions, etc.), and no use of hypnotic drugs.

In the end, it is recommended that future research should endeavor to obtain more accurate results and confirmed the results of this study and eliminate the defects of the present study and consider other health aspects of the wind turbine effects in the wind power plant workers.

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