

Article

Key Concerns and Drivers of Low-Cost Air Quality Sensor Use

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Abstract: Low-cost sensors are revolutionizing air pollution monitoring by providing real-time, highly localized air quality information. The relatively low-cost nature of these devices has made them accessible to the broader public. Although there have been several fitness-of-purpose appraisals of the various sensors on the market, little is known about what drives sensor usage and how the public interpret the data from their sensors. This article attempts to answer these questions by analyzing the key themes discussed in the user reviews of low-cost sensors on Amazon. The themes and use cases identified have the potential to spur interventions to support communities of sensor users and inform the development of actionable data-visualization strategies with the measurements from such instruments, as well as drive appropriate ‘fitness-of-purpose’ appraisals of such devices.

Keywords: low-cost air quality monitors; citizen science; Amazon reviews



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1. Introduction

Air pollution concentrations are collected by networks of expensive, high-quality, fixed-reference monitoring stations that measure a set of ‘criteria’ or widespread pollutants. However, because reference monitors are expensive and can cost several USD 10,000, such networks are sparse. Even the US, which has one of the densest air pollution monitoring networks in the world, only has a regulatory monitor reporting high-quality PM_{2.5} concentrations (mass concentrations of fine particulate matter that has a diameter of <2.5 μm) in ~21% of the 3100 counties.

Low-cost sensors (LCS) (<USD 2500, as defined by the US EPA Air Sensor Toolbox) have the potential to capture concentrations of pollutants in previously unmonitored locations. [1–4]. The relatively low cost of these devices has made them accessible to the public, making them important new players in air quality monitoring. Although LCS measurements have many sources of uncertainty and cannot be used for regulatory purposes, they are increasingly being used to collect real-time, localized data about individuals and their surroundings [5,6]. There are a range of low-cost sensors on the market that are of varying quality, measure different pollutants, have different mechanisms and designs, and present measurements made using a range of metrics through different interfaces.

In the last five years, there have been several studies published that evaluate the various low-cost sensors on the market in laboratory and field conditions for different end purposes. In a literature review of the applications of low-cost sensors, US EPA researchers identified four broad application categories: (1) identification of the spatio-temporal variability of pollutants; (2) comparison of air pollution levels against a threshold value or between networks, areas, and times; (3) identification of long-term trends in pollutant concentrations; and (4) use of data from low-cost sensors for decision support [7]. This review was conducted to aid efforts in developing ‘fitness-of-purpose’ appraisals of the different sensors for these end-use applications.

However, little research exists on how such sensors are used more broadly by the public for non-research purposes and what the “behavioural, socio-political, and ethical implications of introducing sensors into communities” are [8]. Although important research has been conducted on how such tools have been used by specific communities [9,10], there

has been little work done to (1) examine the drivers of sensor use and (2) understand how the general public are interpreting and using the data from such devices. Such work can enable the future design of low-cost sensors and data visualizations to provide easy-to-interpret insights to communities to address key questions or concerns. It can also aid in policy interventions to grow and sustain communities of sensor users.

To address these research needs, this study analyzes product review comments on Amazon (a leading multinational online retailer) for 94 low-cost air quality monitors measuring a range of different pollutants: formaldehyde (HCHO), total volatile organic compounds (TVOCs or VOCs), particulate matter: PM_{1.0}, PM_{2.5}, and PM₁₀, carbon monoxide (CO), carbon dioxide (CO₂), nitrogen dioxide (NO₂), and ozone (O₃), as well as a combined estimate of different pollutants in the form of an air quality index (AQI), in the price range of USD 13.97–USD 329, to identify the key themes that arose when users described their use of the sensor they had purchased.

Infodemiology, the practice of analyzing consumer-sourced qualitative data, such as Amazon reviews, is an emerging area of research that uses freely-available consumer-generated data to provide insights that can be used for making public-health-related decisions [11]. As few data currently exist on the usage of low-cost sensors by the public, the Amazon text reviews and ratings (1–5 stars) of the products can provide valuable insights to policy-makers as a key first step. This paper uses topic modeling, an unsupervised machine learning technique, to extract key topics from the 1000s of reviews downloaded. Essentially, topic models pick up co-occurrence signals between different words in the collection of texts. The underlying assumption is that words that occur often in the same sentence are likely to belong to the same latent topic.

2. Data and Methods

Amazon Standard Identification Numbers (ASINs), blocks of 10 characters that uniquely identify all products sold on Amazon, were scraped for all products listed in the department of ‘Indoor Air Quality Meters’ on Amazon, using the tool Helium10 (<https://www.helium10.com/>, last accessed 25 January 2021) on Monday, 25 January 2021. A manual search for air quality sensors on Amazon indicated that almost all air quality sensors sold on the site were listed under this category. There was no category for ‘Outdoor Air Quality Meters’. The price, overall rating, and number of reviews of each device were also downloaded using Helium10. All the reviews (the text and the star rating) for each device corresponding to the list of ASINs from Amazon were scraped on Monday, 25 January 2021, using ProxyCrawl (<https://proxycrawl.com/>, last accessed 25 January 2021). The total number of reviews obtained was 2707. Ninety percent of these reviews were from users in North America. There were a small number of reviewers from Europe. No additional information on reviewers was available.

This paper reports the descriptive statistics of the reviews and devices considered in this analysis. Specifically, it details the range of pollutants measured, the average rating of each device, and the standard deviation in star ratings.

2.1. Preprocessing

A flowchart that summarizes the preprocessing is presented in Figure 1. A more detailed description of each preprocessing step is now detailed:

- (i) All reviews where the word count was ≤ 25 words were removed. This is because the reviews with less than 25 words contained little information that would be relevant to a topic model. Three reviews that were not in English were removed. One thousand eight hundred and eighty-eight reviews from 94 different monitors remained.
- (ii) Special characters (non-ASCII characters), punctuation, and numbers were also removed from the review text.
- (iii) Stop words, such as ‘the’ and ‘of’ from the SMART stopwords list [12], which are built into the tidytext package in R, were removed [13].

- (iv) After this step, additional stop words from a custom list were removed: { "air", "read", "devic", "unit", "meter", "qualiti", "product", "quality", "device", "monitor", "amazon", "measure", "hcho", "pm", "pm25", "reading", "bought", "readings", "values", "sensor", "data", "change", "compare", "compared", "found", "level", "measure", "results", "levels", "pollution", "check", "highly", "found", "house", "home", "googl", "browser", "html5", "video", "formaldehyd", "formaldehyde", "ppm", "ghz", "pro", "tvoc", "voc", "temperatur", "co2", "hour", "set", "minut", "time", "la", "de", "lot", "el", "la", "particle", "particulate", "one", and "thing" }.

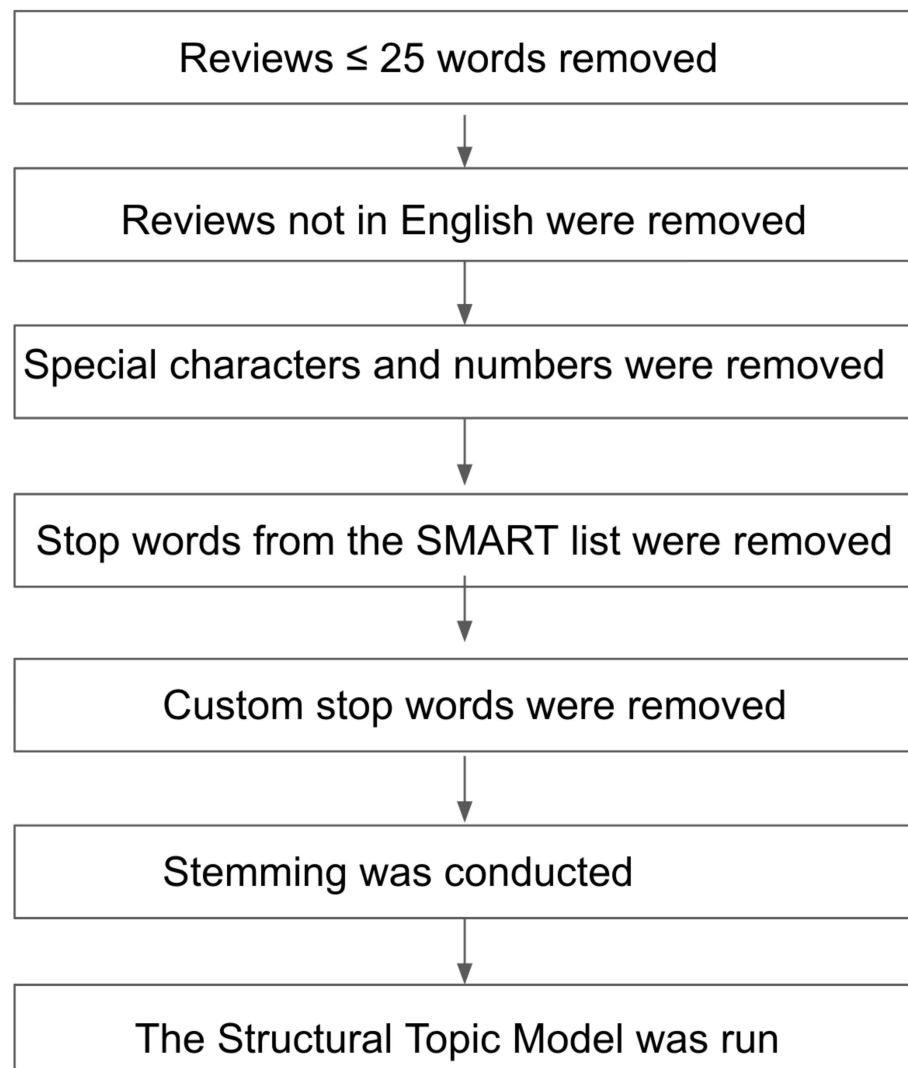


Figure 1. Steps taken to pre-process the text before running the topic model.

Stop words tend to be high-probability terms that can skew the word-type probability distribution and slow inference from the topic models.

- (v) Stemming was used to lemmatize words and their derivatives (e.g., determine, determined, determining), thus rendering all derivative forms of a single word in an unambiguous, non-inflected state. As language exhibits a rich inflectional morphology, if derivatives of the same word are treated as unique tokens, the co-occurrence signal between different words in the corpus under consideration will become weaker. We thus applied stemming to improve the quality of the topic model.

An example of how these pre-processing steps affected the text is as follows:

Before: “Atmotube just arrived! I had downloaded the app ahead of time & it worked great! Easy connection & set up. It has a very solid feel. Nice packaging. I’m looking forward to using this!”

After: “atmotub arriv download app ahead easi connect solid feel nice packag forward”.

2.2. Structural Topic Modeling

Unsupervised machine learning has been commonly used in studies that do not have any predetermined framework to analyze unstructured text data [14–16]. Such topic modeling enables researchers to discover topics from the data. This process may avoid biases generated through non-automated coding that relies on subjective interpretations of the text.

Essentially, a topic model represents the overall themes or topics in a corpus as probability distributions over words in a vocabulary; so, while the probability of the word “smoke” is high in a topic relating to wildfires, it will likely be relatively low in a topic pertaining to the ease of use of a low-cost sensor. Documents (which in this case are reviews) consisting of combinations of words were modeled using a generative process where first a topic is selected according to some probability distribution specific to a given document, and then, a word is selected from that topic in accordance with the topic’s distribution over vocabulary words. Using the documents in this corpus (which are the output of such a generative process), we can infer the likelihood of each topic given a document and each word given a topic through a training process.

Latent Dirichlet Allocation (LDA) is the most commonly used topic model. However, LDA has several limitations, one of the most important being that it assumes that topics are independent of each other. The recently introduced structural topic modeling (STM) algorithm builds on the LDA model and allows topics to be correlated [17]. For a more detailed discussion of STM models, refer to [18]. In this paper, topic modeling was implemented in R with the STM package [19], using the spectral algorithm without the inclusion of covariates [20]. When the number of documents is large, as it is in this case, the spectral algorithm has been shown to perform well and provide more stable and consistent results than the LDA model [19].

To determine the number of topics in the text, this paper used the metrics of held-out likelihood and semantic coherence provided by the STM package. Held-out likelihood (an indication of cross-validation) is calculated by holding out 10% of the words in the corpus, training the model, and using the document-level latent variables to evaluate the probability of the held-out words. Semantic coherence (an indication of higher topic interpretability) measures the frequency of the co-occurrence of the top words of a topic [21]. This paper compared the performance of 5, 6, 7, 8, 9, 10, 15, and 20 topic models using these metrics.

It can be observed that seven topics appear to provide the best trade-off between the greatest coherence and the held-out likelihood (Figure 2). A model with seven topics also withstood the author’s subjective evaluation of the themes produced.

This paper provides brief summaries of each topic derived from the 7-topic model by reporting words with the highest occurrence probability corresponding to a specific topic. However, as some terms, such as “measure”, will have a high occurrence frequency across several topics, they add limited value for topic interpretation. To aid in identifying topics, Bischof and Airoidi (2012) proposed the FREX statistic, defined as the weighted harmonic mean of a word’s rank in terms of its exclusivity and frequency, to identify high-frequency words exclusive to a given topic [22]. This paper accordingly presents the highest-ranked words using the FREX metric to aid in topic interpretation.

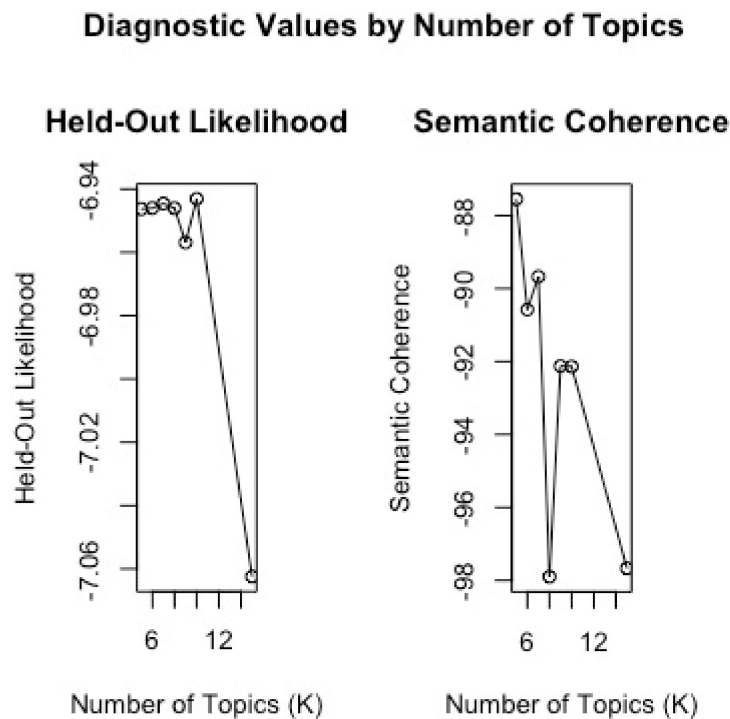


Figure 2. Diagnostics to determine the number of topics.

This article also reports the prevalence of the seven topics over reviews corresponding to (i) different ratings—a proxy of user satisfaction with the device, (ii) different reported pollutants, and (iii) different devices. It must also be noted here that >90% of the devices included in this study measure more than one pollutant (Table 1). It is impossible to tell which pollutant was being discussed in the review. In this analysis, each review was linked with all the pollutants that the corresponding device is reported to measure.

Non-parametric Kruskal–Wallis tests, also termed as one-way ANOVA on ranks (Shapiro tests revealed that the assumption of the normality of the distribution of prevalence of each topic did not hold), were run to evaluate whether the prevalence of each topic varied significantly by the customer’s rating, the device being reviewed, and the pollutants reported. Statistical significance in this study is assessed using a $p < 0.05$ threshold.

Table 1. Unique ASIN number, price, number of reviews, overall ratings, average rating of reviews, std deviation of ratings, min word count, max word count, mean word count, and standard deviation of the word count of reviews considered in this analysis corresponding to each of the 94 low-cost air pollution monitoring devices classified as an ‘Indoor Air Quality Meter’ on Amazon. Almost every device measures multiple pollutants. The various pollutants measured by each device are included in the name of the instrument.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
1	B01BST18LQ	Atmotube 2.0—Portable Air Quality Monitor. Indoor/Outdoor Air Pollution Tracker: PM1, PM2.5, PM10, VOC, Temperature, Humidity, Barometric Pressure	165	35	3.5	3.6	1.46	26	314	84.23	55.95
2	B073VHHNGT	Temtop LKC-1000E Professional Formaldehyde Monitor Detector with HCHO, PM2.5, PM10, AQI Accurate Testing Air Quality Detector	109.99	13	4	3.46	1.76	27	834	167.38	276.28

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
3	B074FTVHFN	Air Quality Monitor, Formaldehyde Detector, Pollution Meter, Sensor, Tester; Detect & Test Indoor Pollution, TVOC, HCHO, PM2.5, Dust; eBook	113.68	175	4	3.32	1.64	26	897	109.26	122.46
4	B0756W25SS	Temtop Airing-1000 Professional Laser Air Quality Monitor PM2.5, PM10 Detector Particle Counter Dust Meter Real Time Display High Accuracy	159.99	9	4	3.33	1.73	34	253	120.89	67.79
5	B076F54XG8	Temtop LKC-1000E Air Quality Monitor HCHO Detector, PM2.5, PM10, AQI Tester	109.99	10	4	3.8	1.75	37	91	68.4	21.43
6	B076PV9X99	uHoo Indoor Air Quality Sensor—9 in 1 Smart Air Monitor with Temperature and Humidity Gauge, CO ₂ , Dust (PM2.5), VOC, NO ₂ , Allergen Meter -to Breathe Easy and Boost Health	329	78	4	3.88	1.54	26	907	156.63	157.15
7	B0778WGMH2	Temtop LKC-1000S+ Professional Formaldehyde Monitor Detector with HCHO, PM2.5, PM10, TVOC Accurate Testing Air Quality Detector	153.99	22	4.5	3.55	1.57	26	281	102.86	70.26
8	B077D1W9RB	Portable PM2.5 Meter Detector Monitor Air Quality Detect High Accuracy Easy Operation	56	1	2	3	NA	169	169	169	NA
9	B077HRXWGP	Temtop LKC-1000S+ Air Quality Monitor Formaldehyde Detector, Air Pollution Sensor, Humidity and Temperature Meter Tester with PM2.5, PM10, HCHO, AQI, TVOC Histogram	153.99	42	4	3.48	1.61	27	611	122.67	120.88
10	B077HWMZ83	Temtop LKC-1000S Air Quality Monitor Formaldehyde Detector, Air Pollution Sensor, Humidity and Temperature Meter Tester with PM2.5, PM10, HCHO, AQI Sensor Indoor Testing	135.99	12	4	3.67	1.72	30	270	82.25	83.7
11	B077JWYJTV	Kaiterra Laser Egg+ Chemical: Indoor Air Quality Monitor (Tracks PM2.5, TVOC, Temperature, and Humidity)	199	57	4	3.91	1.44	27	942	141.4	167.01
12	B0784TZFRW	IQAir AirVisual Pro Air Quality Monitor for PM2.5, CO ₂ , AQI, Temperature, and Humidity, IFTTT App Enabled, Real-Time Air Quality	269	87	4	3.51	1.74	28	621	122.57	95.78
13	B07878CP8L	Temtop P200 Air Quality Laser Particle Detector Professional Meter Accurate Testing for PM2.5, PM10 LCD Display	64.89	16	4	3.38	1.67	31	356	110.81	86.53

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
14	B0787Z5DK9	Temtop P600 Air Quality Laser Particle Detector Professional Meter Accurate Testing for PM2.5, PM10 TFT Color LCD Display	98.99	32	4	3.91	1.33	27	738	91.41	123.54
15	B079FR4HMB	ECOWITT WH0290 Air Quality Monitor Meter PM2.5 Detector Indoor Outdoor with Temperature and Humidity for Home Office Car	69.99	32	4	3.62	1.68	27	235	80.25	51.64
16	B079GS8XHY	Temtop LKC-1000S Professional Formaldehyde Monitor Temperature and Humidity Detector with PM2.5, PM10, HCHO, AQI Accurate Testing Air Quality Detector	135.99	5	4.5	3.8	1.64	27	110	70.6	36.31
17	B07B7KLMVW	Air Quality Monitor, IGERESS Indoor Air Pollution Tester for Formaldehyde TVOC PM1, PM2.5, PM10, Temperature and Humidity, Real Time Home Air Quality Detector Meter, Colorful LCD Screen	110.99	38	4	3.71	1.52	27	277	97.45	68.04
18	B07B8LNGFT	Air Quality Monitor Sherry Indoor Air Quality Monitor for CO ₂ , HCHO, TVOC, PM2.5, PM10 -Accurate Air Quality Monitor Indoor Radar Detectors	109.9	79	4	3.42	1.46	26	1176	164.96	197.63
19	B07DGVYW3C	Air Quality Monitor ind CEM DT-968 Accurate Tester for CO ₂ , HCHO, TVOC PM2.5, PM10 Multifunctional Air Gas Detector Real Time Data & Mean Value Recording for indoor	119.99	4	3	3.5	1.73	33	120	77.5	35.93
20	B07DGWZS3Q	CEM DT-9681 Indoor PM2.5, CO ₂ , HCHO Air Quality Meter Particle Mass Concentration Monitors with LCD Display Testing HCHO, PM2.5, PM10, CO ₂ , Humidity and Temperature Real Time Monitoring	156.04	1	3.5	3	NA	85	85	85	NA
21	B07DHXQXGK	Temtop M10 Air Quality Monitor for PM2.5, HCHO, TVOC, AQI Professional Electrochemical Sensor Detector Real Time Display Rechargeable Battery	89.99	47	4.5	3.68	1.6	27	538	99.38	89.66
22	B07DHW6YD	Temtop M1000 Air Quality Monitor for PM2.5, HCHO, TVOC, Temperature and Humidity Detector Large LCD Display Built-in Rechargeable Battery	116.99	13	4	3.77	1.17	26	456	140.54	143.08
23	B07DHZ3MFR	Temtop P1000 Air Quality Monitor for PM2.5, PM10, CO ₂ , Temperature, Humidity Indoor Detector Large LCD Display Built-in Rechargeable Battery	120.99	11	3.5	3	1.67	27	400	113.18	118.2

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
24	B07DJ1WCVP	Temtop M2000C Air Quality Monitor for PM2.5, PM10, CO ₂ , Temperature and Humidity settable Audio Alarm Recording Curve Easy Calibration Colorful Display	153.99	19	4.5	3.89	1.29	31	1011	112	225.19
25	B07DL1M46J	2.8" Digital Car PM2.5 Air Quality Detector Tester Meter AQI Home Gas Monitor	55.99	33	4	4.3	1.13	26	298	98	68.95
26	B07G9PTQW6	Flow, The Personal Air Quality Sensor by Plume Labs—Mobile, Bluetooth Connection, Measures PM2.5, PM10, NO ₂ , VOC Indoors and Outdoors	119.99	45	3.5	3.4	1.56	34	601	149.6	118.39
27	B07GDR4N6P	Kaiterra Laser Egg: Indoor Air Quality Monitor (Tracks PM2.5, Temperature, and Humidity)	149	8	3.5	3.38	1.85	47	194	93.12	46.12
28	B07H3NXNDV	BTMETER—Air Particulate Meter PM2.5 PM10 Monitor Meter BT-5800D Pro Particulate Matter Detector, Accuracy +/- 20% Tester for Air Quality Monitoring Indoor Outdoor w/Back Light	99.99	5	4	3.8	0.45	34	475	193.6	180.94
29	B07H8WXYZ8	Temtop LKC-1000S+ Air Quality Monitor Formaldehyde Detector, Air Pollution Sensor, Humidity and Temperature Meter Tester with PM2.5, PM10, HCHO, AQI, Particles, TVOC Histogram	153.99	14	4	2.86	1.75	35	397	145.64	113.65
30	B07J1QF8XB	CEM DT-9681W Indoor Air Quality Meter Particle Mass Concentration Monitors with WiFi Function LCD Display Testing HCHO, PM2.5, PM10 CO ₂ , Humidity and Temperature	239	1	5	5	NA	113	113	113	NA
31	B07JLRJRLN	ECOWITT WH41 PM2.5 Air Quality Sensor Monitor Indoor Outdoor—Accessory Only, Can Not Be Used Alone	47.99	9	4	3.56	1.67	26	762	187.44	225.97
32	B07NVN288W	TOPINCN Portable Formaldehyde Detector Indoor Home Digital Hand-Held Air Quality Tester HCHO Meter, TVOC Monitor, PM2.5, Benzene	17.49	3	3.5	3.33	2.08	51	639	257	331.16
33	B07P7FV16F	Air Quality Monitor Formaldehyde Detector, Indoor Pollution Meter, Tester, Sensor, Temperature and Humidity, Air Detector PM2.5, PM10, HCHO, TVOC Real-Time	112.99	54	4	3.67	1.59	26	578	121.81	118.18
34	B07R2C23RH	TVOC Air Quality Monitor Detector Pollution Meter Monitor to Detect Indoor Pollution 2020 New Indoor air Quality Monitor	NA	21	3.5	4.24	1.18	27	272	82.05	73.5

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
35	B07RKYLMTD	Huma-i (HI-150), Advanced Portable Air Quality Monitor Indoor Outdoor Which Measures CO ₂ , VOC, PM2.5, PM10, Temperature, Humidity—Black	149	44	4.5	3.75	1.4	29	908	129.77	154.92
36	B07TGD2DMR	Finetoknow Portable Air Quality Monitor HCHO, TVOC, PM2.5, PM10, HCHO Detector LCD Display Tester	13.97	1	1	1	NA	140	140	140	NA
37	B07VGH8ZP9	HeiYi Air Quality Monitor, Air Quality Tester Accurate PM2.5, Temperature, Humidity Monitoring Smart Air Quality Detector Indoor Outdoor Real Time LCD Display	49.99	7	4	3.86	1.57	32	597	180.29	216.68
38	B07VQDS3V7	Goplus Air Quality Pollution Monitor, 7 in 1 Indoor HCHO Detector, Temperature & Humidity Meter Tester, Detects TVOC, PM2.5, PM10, PM1.0	86.99	5	4	3	2	46	161	87.8	51.06
39	B07W832542	HOLDPEAK Air Quality Tester, PM2.5, PM10 Detector Accurate Air Quality Monitor with Dot-Matrix LCD, use for Home, Industry and Various Occasion (HP-5800D)	90.99	1	4	4	NA	82	82	82	NA
40	B07WD5GGZK	Atmotube Pro Portable Outdoor and Indoor Professional Air Quality Monitor (PM1, PM2.5, PM10, VOC, HCHO, Temperature, Humidity and Barometric Pressure Gauge)	169	58	4	4.16	1.12	26	727	166.67	161.21
41	B07WZFX4S	Air Quality Monitor HT9600 PM2.5, PM10, Air Quality Analyzer Humidity Meter Handheld Particle Counter Monitor for Indoor Environment of Family, Office, Inside of Cars and Natural Environment, etc.	170.19	1	3	1	NA	30	30	30	NA
42	B07XB4C735	AirRadio Smart Indoor Air Quality Monitor (Temperature, Humidity, PM2.5, PM10) Home dust Concentration Detector, Volcanic ash Meter Monitor with Storage Case (APP)	39.99	2	3	1	0	33	58	45.5	17.68
43	B07ZH8FGND	FUELUS Air Quality Tester, Detector, HCHO, PM2.5, PM10, TVOC Monitor Suitable For Indoor, Outdoor Environmental Air Detection	NA	4	2.5	3	2.31	48	232	128.5	76.32
44	B07ZM1K3XV	Air Quality Monitor Meter IGERESS Multifunctional Air Quality Tester Accurate Detector Indoor with Holder for HCHO, TVOC, PM2.5, PM10 (Gray)	105.99	25	3.5	3.72	1.57	28	501	83.12	99.55

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
45	B081VDVY7B	iClever Air Quality Monitor, Wireless Chargeable Air Quality Tester for PM2.5, PM10, PM1.0, Temperature, Humidity, Indoor Outdoor Air Detector for Home/Office/Car and Various Occasion (White)	59.99	26	3.5	3.54	1.39	34	1614	208.08	304.45
46	B081X63K3B	Air Quality Monitor Indoor, Accurate Air Tester Detector(3000mAh) for HCHO, CO ₂ , TVOC, PM2.5, PM10, Home Air Test Kits with Colorful LCD Screen, Suitable for Home Office and Various Occasions	95.99	19	4	3.53	1.43	27	137	63.58	33.76
47	B082HCWND5	Air Quality Tester, Detector, Multi-Functional HCHO, PM2.5, PM10, TVOC Monitor, Suitable for Indoor, Outdoor, Vehicle and Other Environmental Air Detection by FUELUS	49.98	7	3	2.57	1.72	39	212	89.43	63.8
48	B082HH9SXY	SEAN Air Quality Monitor Indoor for TVOC, HCHO, CO ₂ , PM2.5, PM10 Portable Air Quality Meters Tester Detector Sensor Real Time Data & Mean Value Recording for Home Office Outdoor	49.99	7	4	4	1.53	26	109	52.43	27.89
49	B082ZF4H37	Awair Element Indoor Air Quality Monitor measuring CO ₂ , TVOC, PM2.5	149	40	4.5	3.5	1.77	27	507	99.92	87.66
50	B0832MW62L	Handheld Air Quality Monitor, High Accuracy Air Quality Tester for HCHO, TVOC CO ₂ , PM2.5, PM10 Monitoring, HD Data Real-time and Mean Value Display, Fits Home Office	NA	9	3.5	3.78	1.64	29	230	68.67	62.8
51	B0834T7JBY	QekTech Air Quality Monitor, Professional Humidity, Temperature, TVOC, and HCHO Pollution Tester for Home, Indoor and Outdoor awair Test kit Meter; Supports PM2.5, PM1.0, PM10	99.99	5	4	4.2	1.1	28	110	62.2	37.9
52	B083HFRC3N	Air Quality Monitor Sherry Indoor Air Quality Monitor for CO ₂ , HCHO, TVOC PM2.5, PM10 -Accurate Air Quality Monitor Indoor Radar Detectors	109	16	4	4.38	1.36	26	251	74.25	58.25
53	B083J1RC56	Air Quality Monitor, Seesii Multifunctional Indoor Pollution Detector Meter for HCHO, PM2.5, PM1.0, PM10, TVOC, Temperature and Humidity AQI Test, Real Time Air Tester	72.9	7	4	4	1.15	48	163	98.43	54.03
54	B083LKSG1X	Multifunctional Air Quality Tester, Sherry Air Quality Monitor, Indoor Formaldehyde Detector Air Quality Monitor Indoor for TVOC, PM2.5, PM10	109	15	4	3.93	1.83	28	279	93.13	74.68

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
55	B084JCXZ12	Guard Dog Security Air Quality Monitor—TVOC, PM1.0, PM2.5, PM10, Temperature & Humidity—Rechargeable Battery	112.99	2	3.5	2.5	2.12	66	100	83	24.04
56	B084N7ZRMJ	Air Quality Monitor BIAOLING Accurate Tester for CO ₂ , HCHO, TVOC PM2.5, PM10 Multifunctional Air Gas Detector Real Time Data & Mean Value Recording for Home Office and Various Occasion	79.99	111	4	4.03	1.43	26	364	93.9	67.79
57	B084X9KTJN	BREATHE Smart 2 Personal Air Quality Monitor, Instantly Measures Air Quality Levels. Monitors Dust, Smoke, PM2.5 Air Pollution—Reduce Your Exposure to Toxic Air	139	55	4	4.38	0.99	27	752	215.38	164.5
58	B085C45TX9	Temtop M2000 2nd Generation PM2.5, PM10, CO ₂ , HCHO Air Quality Monitor Data Export Settable Audio Alarm Recording Curve Easy Calibration Temperature Humidity	215.99	4	5	5	0	40	198	112.25	71.14
59	B085C4KRH4	Temtop M2000 2nd Generation Air Quality Monitor for PM2.5, PM10, CO ₂ , HCHO Temperature, Humidity Settable Audio Alarm Data Export Recording Curve Easy Calibration	215.99	41	4.5	3.8	1.52	26	440	110.71	75.63
60	B085N5VZXB	seeed studio Air Quality Monitor Indoor, Air Quality Testor, HCHO, Detector Real-Time Air Tracking for TVOC, PM2.5, PM10, Air Quality Detector for Home/Office/Car (White)	69	15	4	3.47	1.46	26	862	133.13	211.37
61	B087N55K5H	Stellate Indoor Air Quality Monitor Detector Sensor HCHO, TVOC, PM2.5, AQI Index Pollution Temperature Humidity Portable for Home Office (AQ200-Stylish)	85.49	50	4	3.84	1.38	26	433	100.86	85.47
62	B087R7C88T	Air Quality Monitor Indoor, Accurate Air Tester Detector for HCHO, CO ₂ , TVOC, PM2.5, PM10, Temperature, Humidity Monitor Analysis Tester Gas Detector Analyzer Measuring Tool Smog Meter	95	2	4	3	1.41	112	157	134.5	31.82
63	B088WBCDXS	Air Quality Monitor Accurate Tester for CO ₂ , HCHO, TVOCl, AQI Multifunctional Air Gas Detector Real Time Data & Mean Value Recording for Home Office and Various Occasion	69.99	44	4	3.57	1.59	27	883	103.07	157
64	B088WT6YD1	CO ₂ Detector Infrared Sensor LCD Display PPM Meters Indoor Gas Air Quality Monitor Analyzer Data Logger USB/Battery Power (External Non-Conductive Data)	129.99	3	4.5	4.33	0.58	27	1190	503.33	609.36

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
65	B088ZTJDB9	Air Quality Monitor-Accurate Tester for HCHO, TVOC, CO ₂ , CO Multifunctional Air Gas Detector Real Time Data & Mean Value Recording for Home Office and Various Occasion (White)	54.7	11	3.5	2.64	1.75	27	190	65.36	50.9
66	B08BCRR7N9	Air Quality Monitor TVOC, HCHO Detector. PM2.5, PM1.0, PM10 Pollution Meter for Home Office School Restaurants and Hospitals	79	3	3.5	3.33	1.53	83	429	207.33	192.44
67	B08CN7FSCG	BRWISSEN A16 Air Quality Monitor Indoor Pollution Tester Data Record for PM1.0, PM2.5, PM10 Particulate Matter Fine Dust Meter, TVOC, HCHO Analyzer Detector	175.99	3	4	5	0	80	219	127.67	79.12
68	B08CZL1RQ4	AOUSTHOP Indoor Air Quality Sensor, Air Quality Monitor, CO ₂ , HCHO, TVOC PM2.5, PM10 Multifunctional Gas Detector, Accurate Tester Kit for Home Office, Real Time Data Mean Value Recording	43.99	6	4	3.33	1.97	32	436	133.33	151.22
69	B08DKTNTHS	Air Quality Monitor, Accurate Air Tester Detector for HCHO, CO ₂ , TVOC, PM2.5, PM10 with Colorful LCD, Portable Air Gas Detector Sensor Real Time Data & Mean Value Recording for Indoor Home Car	79.99	2	3	2	0	79	281	180	142.84
70	B08DLL3WFN	Tusingger Air Quality Monitor Accurate Tester for CO ₂ , HCHO, TVOC PM2.5, PM10 Multifunctional Air Gas Detector Real Time Data & Mean Value Recording for Home and Various Occasion	53.99	8	4.5	4.75	0.46	85	360	204.12	101.06
71	B08DRHKYSR	Air Quality Monitor Yvelines Air Quality Tester for CO ₂ , HCHO, TVOC, PM2.5, PM10 Multifunctional Air Gas Detector Real Time Data & Mean Value Recording for Home Office and Various Occasion	97.99	53	4	4.06	1.59	28	479	86.83	71.65
72	B08F9W3XRF	Air Quality Monitor, Elifecity Indoor Tester for HCHO, TVOC, PM2.5, PM10 Humidity and Temperature Meter Multifunctional Air Gas Detector for Home Office School and Car	69.99	4	4.5	4.5	0.58	33	95	55	27.8
73	B08FDTD3CR	Air Quality Monitor HCHO, TVOC, AQI, CO, CO ₂ 5-in-1 Multifunctional Detector Monitor Outdoor and Indoor for Home Office Baby Room Various Occasion, White Air Quality Test	49.99	3	4.5	4.33	0.58	28	54	37.67	14.22

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
74	B08FHYHFTN	Air Quality Monitor Accurate Tester for PM2.5, PM10, PM1.0, Temperature and Humidity, Rechargeable Electrochemical Air Gas Sensor Detector Real Time Data & Mean Value Recording for Home Office Indoor Outdoor	59.49	3	3.5	2.33	2.31	38	200	112.33	81.82
75	B08FXSWHVG	Davis Instruments AirLink Professional Air Quality Sensor measuring PM1, PM2.5, PM10	178.99	6	4	3.83	1.83	29	513	138.33	188.57
76	B08FZV3M3P	WiFi Air Quality Monitor Indoor CO ₂ Detector Gas Pollution Real Time Tester for PM2.5, HCHO, TVOC, Temperature and Humidity, Colorful LCD Screen, Rechargeable Battery	99.98	14	3	2.93	1.69	35	178	86.86	49.73
77	B08GLV1YP7	ATPRO Indoor Air Quality Monitor, HCHO Formaldehyde Detector, Temperature & Humidity, Pollution Tester & Sensor, Measure TVOC, PM1.0, PM2.5, PM10	98.95	8	4.5	4.62	1.06	59	305	157.12	84.45
78	B08J2Y7HL6	Air Quality Monitor, HCHO Detector, Pollution Meter, Sensor, Tester; Detect & Test Indoor Pollution, VOC, PM1, PM2.5, Air Quality Monitor	75.99	9	4	3.78	1.56	42	215	97.11	53.82
79	B08J3KL7TJ	Air Quality Monitor Indoor, Air Quality Tester for HCHO, PM2.5, PM10, Temperature, Humidity, Colorful LCD Screen with ECO Features, Suitable for Home Office and Various Occasion (White)	99.99	3	3.5	4.67	0.58	100	510	252.67	224.15
80	B08JM4BR8J	Air Quality Monitor, HeiYi Indoor Air Quality Pollution Detector for HCHO, TVOC, PM2.5, PM1.0, PM10, Temperature, Humidity Data Monitoring, Meter 24-Hour Real-Time Recording	79.99	16	4	4.31	1.01	39	2260	243.5	541.16
81	B08JXD3JZT	Air Quality Monitor YVELINES Air Quality Tester for CO ₂ , HCHO, TVOC, PM2.5, PM10 Multifunctional Air Gas Detector Real Time Data & Mean Value Recording for Home Office and Various Occasion	114.99	16	4.5	3.69	1.78	28	173	69.56	46.67
82	B08K8VS5GY	VIVOSUN Air Quality Monitor Indoor Pollution Detector HCHO Tester, TVOC and PM2.5, PM10, PM1.0 temperature and humidity Sensor Function	79.9	12	4.5	4.67	0.65	29	304	85.92	75.34
83	B08KSX9WG3	Hofun Air Quality Monitor—Professional Air Quality Detector, 5 in 1 Indoor Air Pollution Tester with AQI, PM2.5, PM10, HCHO, TVOC, Air Particulate Meter for Home, Car, Office, Hotel	98.01	7	3.5	3.57	1.51	29	320	125.29	105.55

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
84	B08L18M9Z6	Air Quality Monitor, HCHO Detector, Temperature & Humidity Meter, Pollution Tester, Sensor; Detect PM2.5, PM10, PM1.0, Test Indoor TVOC	99.99	2	3	4	1.41	43	137	90	66.47
85	B08L2ZFTQ6	Air Quality Monitor, Accurate Tester for HCHO, TVOC, PM2.5, PM1.0, PM10, Temperature and Humidity for Home, Office and Various Occasion	69.99	3	4	4.33	0.58	42	110	72.33	34.59
86	B08L96TX6Z	Air Quality Monitor, HCHO Detector, Temperature & Humidity Meter, Pollution Tester, Sensor; Detect PM2.5, PM10, PM1.0 Test Indoor TVOC	95.99	3	4	3.33	2.08	31	86	56.33	27.75
87	B08LL96J6Q	Air Quality Monitor, HeiYi PM2.5 Air Quality Tester Highly Accurate Real Time Monitoring Smart Air Quality Detector Indoor Outdoor LCD Display	69.99	3	3.5	3.67	2.31	37	73	57	18.33
88	B08M5S11TG	Air Quality Monitor, SeeSii Indoor Air Quality Pollution Detector for HCHO, TVOC, PM2.5, PM1.0, PM10, Temperature, Humidity Data Monitoring, Real-Time Recording for Home Office Classroom	62.9	2	3.5	3	2.83	85	209	147	87.68
89	B08MVK38G8	Air Quality Monitor, Seesii 8-in-1 Multifunctional Air Quality Tester for HCHO, TVOC, CO ₂ , PM2.5, PM10, AQI, Temperature Humidity, Indoor Outdoor Air Gas Detector for Home/Office/Car and Various Occasion	85.99	2	5	3	2.83	63	64	63.5	0.71
90	B08MY3J85D	Air Quality Monitor, HCHO Detector, Indoor Pollution Meter, Tester, Sensor, Temperature and Humidity, Multifunctional Air Detector PM2.5, PM10, HCHO, TVOC Real-Time	99.99	7	4.5	4.43	0.98	30	172	103.14	48.78
91	B08P3QCHNS	Air Quality Monitor, Handife Air Quality Tester for PM2.5, Temperature (−10~50 °C) and Humidity (0%~99% RH) Monitor Highly Accurate Smart Portable Air Quality Detector Indoor Outdoor LCD Display	45.99	5	3.5	4.6	0.89	32	96	48.8	26.66
92	B08P4QN2NN	HYVQDNM Air Quality Monitor Indoor for CO ₂ , CO, HCHO, TVOC PM2.5, PM10 Multifunction Air Quality Detector Real Time Data & Mean Value Recording Air Gas Detector for Home Office Car School etc	102.99	3	5	5	0	29	164	77.67	74.97

Table 1. Cont.

	ASIN	Name	Price (USD)	No. Reviews	Overall Rating	Mean Rating	Std Dev of Rating	Min Words	Max Words	Mean Words	Std Dev Words
93	B08PYTRRY2	Air Quality Monitor PM2.5, PM10, PM1.0 Tester, HCHO, TVOC, temperature, humidity Detector, Air Quality Tester	79.99	6	5	5	0	32	128	74.33	40.55
94	B08Q3RJBLR	Air Quality Monitor Indoor & Outdoor for PM2.5 Particulate Matter, BAIVON Air Quality Tester Pollution Detector Meter for Home Office Car Travel Use Etc	79.99	8	5	4.5	1.41	46	134	89.12	33.7

3. Results

Table 1 provides a summary of the 1888 reviews of the 94 low-cost air quality monitors sold on Amazon as well as their price and average rating. Three monitors were no longer being sold, and therefore, information about their price was not available.

Each air quality monitor reported a range of different pollutants. Sixty-two reported HCHO concentrations, 55 reported TVOC concentrations, 89 reported PM_{2.5} concentrations, 68 reported PM₁₀ concentrations, 23 reported PM₁ concentrations, 1 reported O₃ concentrations, 2 reported NO₂ concentrations, 6 reported CO concentrations, and 36 reported CO₂ concentrations. Almost all the monitors reported an Air Quality Index (AQI) Value of some form, though these were not consistent.

The accuracy of many (specifically, the brands Elitech (Temtop), uHoo, Awair, AirVisual, Ecowitt Kaiterra, Atmotube, and Flow), but not all, of the 94 monitors, in reporting ‘criteria’ or wide-spread pollutants (PM_{2.5}, PM₁₀, NO₂, O₃, CO), have been evaluated by regulators or academics in the lab and in the field [23,24]. According to these evaluations, different sensors have varying levels of performance. For example, the PM_{2.5} concentrations measured using the Kaiterra Laser Egg agree reasonably well with the high-quality alternative ($R^2 \sim 0.8$), while the PM_{2.5} readings of the Plume Labs Flow 2 sensor did not do as well ($R^2 \sim 0.1$) [23]. There was little information on the performance of each device in measuring non-criteria pollutants such as HCHO and TVOCs.

The customer reviews of the devices did not correlate well with the reported evaluations by the EPA. For example, the Flow sensor and the Kaiterra Laser Egg sensor, measuring only PM_{2.5} (ASIN: B07GDR4N6), both had an overall rating of 3.5 (Table 1). For the reviews included in this analysis, the average ratings were 3.4 and 3.38, respectively, with a mean (median) standard deviation in the ratings for both devices of 1.2 (1.5) (Table 1). Different users thus have vastly different experiences with the same device. In order to understand the different dimensions of the users’ experience with the different low-cost air quality sensors, this paper now reports the seven themes that arose from analyzing the customer reviews.

The word clouds for each topic depicting the words with the highest probability of occurrence are presented in Figure 3. The larger the font, the higher the probability of the occurrence of the word for the given topic. The prevalence of each topic (or the proportion of each topic in the entire corpus), words which scored highly on the FREX statistic, as well as the representative reviews corresponding to each topic, are displayed in Table 2.

Table 2. The prevalence, word clouds, high probability key words, and representative excerpts from customer reviews for each topic.

Topic	Topic (Prevalence)	Topics Based on FREX	Representative Excerpts	
1	Wildfire Smoke	0.176	fire, filter, purifi, california, insid, season, open	<p>“Bought this to see how our air filters were working against the wildfire smoke. The image on the left is in front of a high quality HEPA filter and the image on the right is after two minutes outside in the smoky air. Good news is our filters work, but the bad news is how awful the smoke is. I would say this is very accurate and helpful for determining what works in our home and what does not (air quality wise anyway).”</p> <p>“With the recent wildfires in California I could not rely on my instinct about air qualities. What I needed was a good estimate of the air quality in my city and my house so I can at least know whether it is a good idea to open the window or not. This little machine does just what I need. It tells me to open up the window for better air or it is better to shut closed. It does connect to your phone and the app is easy to follow. I assume that the app is operated in several languages since mine started with Korean in the beginning.”</p>
2	Detecting sources of concern	0.168	compound, paint, odor, furniture, substance, organic, detector	<p>“This device may be useful for some things, but the description exaggerates its capabilities. The description claims that the device can measure TVOC which is an abbreviation for “total volatile organic compounds.” However, I did a number of tests and while it is clear that it detects some VOCs, it does not detect others (for example, the VOCs released by some glues). 2) The Formaldehyde (labelled HCHO on the device) detector is not useful for detecting the real amount of formaldehyde. While it may be triggered by formaldehyde, it also detects many other common VOCs that are not formaldehyde. For example, it seems to be triggered by isopropyl alcohol (a disinfectant commonly used in first aid and medical applications).”</p> <p>“Just bought new furniture and want to make sure there was no harmful gases off them. This unit is easy to use, but make sure to wait 1 hr for the results to reach equilibrium. Results look pretty accurate.”</p>
3	IOT issues	0.159	app, wifi, network, email, android, iphone	<p>“Potentially great product ruined by bad software, onboarding. I am a Cisco Certified Network Professional with decades of network and IT experience. I also develop IOT in my spare time, and have tons of home automation experience. When I say this thing is a failure, I am not joking. The fundamental flaw is trying to “Magically” “Make Easy” the addition of IOT devices like this. They TRY to leverage your existing WiFi account information. ”</p> <p>“It does what it should and, in my opinion, very well. However, there is a star deduction because I could not set up the device with an Android mobile phone because the app had constantly lost the connection to the device. When I tried the setup with an iPhone, it worked immediately and without any problems.”</p>
4	Ease of use	0.135	color, quiet, instructions, easy, operate, simple	<p>“For me, it is a good device to get an overview of pollutants or loads. However, I am not very sure about the accuracy of the data really. Unfortunately, the device does not have a meaningful operating manual and so it is really not easy to use. Assessing or evaluating the data is then also difficult. You have to try out a lot, read on and then derive the data yourself, whether it is precise or at all meaningful. All in all a bit difficult and for me not necessarily the point.”</p> <p>“It is easy to use. I bought it to check the air quantity of my new house. I once felt difficult to understand the terms, but this product is easy to use. The handbook is also easy to understand. Generally, it is easy to handle.”</p>
5	Managing health	0.131	allergies, cough, husband, wood, exhaust, vent	<p>“Grandma often has bad lungs and coughs easily. She took a lot of medicine, she had a lot of treatment, but nothing worked very well. It was probably because she was old and had seen it by chance. I think my grandmother needs it. For the old people, the surrounding environment cannot be ignored, so I decided to buy it, the results of its display shocked us, originally with our life can not live without so many harmful factors in the air, we are glad to choose it.”</p> <p>“This device saved my dads life! So for the past year or so my dad have been feeling not so good. Soar through dizzy nauseous. Well during the COVID lock down it got 10 times worse. He spent thousands of dollars on air cleaners trying to remove dust as he thought he had allergies. When nothing worked we thought it might be VOC’s from some flooring we did last year. Once we hooked the device up it immediately indicated CO₂ levels were at almost 1900 parts per million anything over 1000 parts per million can make you sick. We traced it back to an improperly burning gas fireplace. He was suffering for CO₂ poisoning. Once we shut the gas off to the fire place the part per million dropped to just over 700. I strongly recommend this device.”</p>

Table 2. Cont.

Topic	Topic (Prevalence)	Topics Based on FREX	Representative Excerpts	
6	Battery Life	0.119	batteries, recharging, configure, usb, charger	<p>“When I use the provided USB cable, with a 2.0 amp USB charger, a lightning bolt shows up on the battery indicator for a half second; it then disappears. Using a different USB cable and charger, the lightning bolt appears, flashes regularly, and the battery indicator appears to be filling up (one bar, two bars, 3 bars, etc).”</p> <p>“Worked well enough, until it spontaneously died after 6 months of use. Now it will not even turn on. Next time I will buy a more reliable product.”</p>
7	Evaluating accuracy	0.112	inaccuracies, consistency, comparison, accuracies, count, epa, standard	<p>“I have changed my rating from 1 star to 2 stars. I have determined that for the unit I have the PM_{2.5} readings are reasonably accurate. However, the inaccurate PM₁₀ readings (as discussed below) are a major deficiency. This is one of those occasions when I wonder how the product gets such good ratings. The PM₁₀ reading is always approximately 1.4 times the PM_{2.5} reading (as also noted by another reviewer). It varies from the 1.4 ratio very little. The readings I get (outdoors) with this meter are reasonably close to the local air quality values for PM_{2.5} but are WAY TOO LOW for PM₁₀.”</p> <p>“The unit is simple and appealing, and allows you to adjust gain and bias (slope and intercept of the calibration, notably for the PM_{2.5} particle counter, which is why I bought the unit.) Near me there are a number of PurpleAir airborne particle monitors, which agree with one another, each has a dual laser for accuracy, and they agree approximately with the one EPA monitor a few miles away. But I can not get my unit to match those readings; it reads too low even if I set the gain (percent) to its max of 30%.”</p>

Briefly, from reviewing Figure 3 and Table 2, the topics identified correspond to the following. *Wildfire Smoke*: Users bought their devices to understand the smoke infiltration into their homes during the wildfire season. Several reviewers discussed using their devices to determine if it was safe to open windows and when to turn on their air filters (*Topic 1*). This was the most prevalent theme that emerged from this analysis. *Detecting sources of concern*: Users bought their devices to detect the impacts of specific sources, such as new furniture, paint, mold, etc. Many reviewers reported how sensitive their devices were to the source in question (*Topic 2*). *Internet-of-Things (IOT) issues*: Users discussed the ease of access of the data from their devices, using mobile apps/web browsers, etc. (*Topic 3*). *Ease of use/Curiosity*: Users were curious about the air they were breathing and bought monitors to understand the pollution levels in the air. These users tended to comment on the ease of use of their devices and how difficult it was for them to meet their objectives (*Topic 4*). *Managing Health*: Several customers bought devices to monitor air pollution because they had allergies or suffered from health conditions that rendered them susceptible to the impact of poor air quality. They used their devices to monitor pollution to control their health conditions (*Topic 5*). *Battery life*: Many customers were disappointed by the battery life of their devices. This was especially important for users who wanted to use their devices in a portable manner and monitor pollution in different locations (*Topic 6*). *Evaluating the accuracy of their devices*: Many reviewers compared the measurements from their devices with the regulatory readings for their areas or nearby PurpleAir monitors, a widely used low-cost sensor [25] to evaluate the accuracy of their devices. They discussed this in their reviews (*Topic 7*).

The Kruskal–Wallis tests revealed significant variation in the prevalence of each topic in the reviews by rating and product. The prevalence of different topics in the reviews corresponding to different ratings is displayed in Figure 4A. The users that had written reviews that mainly discussed using their devices to track fires (*Topic 1*), managing their health (*Topic 5*), and the ease of use/curiosity (*Topic 4*) tended to be positive about the device they had bought (their ratings tended to be 4 or 5 stars). On the other hand, the reviews that mainly discussed the accuracy of their instruments (*Topic 7*), battery life (*Topic 6*), and IOT issues (*Topic 3*) tended to correspond to low ratings (their ratings tended to be 1 or 2 stars) in comparison to other data.

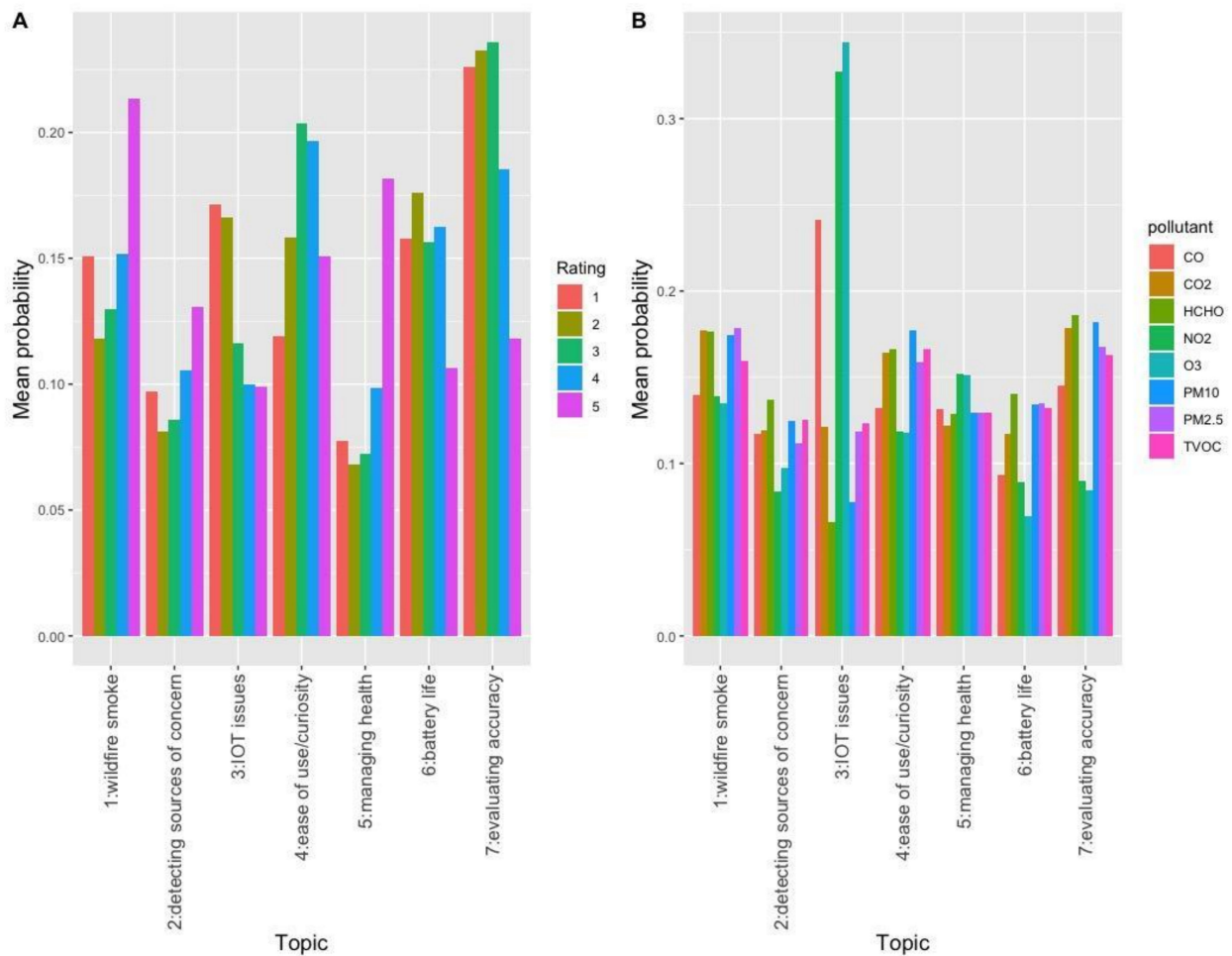


Figure 4. The mean estimated proportion of words corresponding to each topic (topic prevalence) for (A) reviews associated with different ratings and (B) different pollutants measured by the device being reviewed.

The mean prevalence of each topic corresponding to the pollutant(s) measured by the device being reviewed is displayed in Figure 4B. The Kruskal–Wallis tests that examined variation in the prevalence of different topics by pollutant were less informative. Overall, we saw little variation in topic prevalence by pollutants. This is likely because almost all the devices measure several pollutants (e.g., 59 of the 94 devices measured both PM_{2.5} and HCHO, two very different pollutants). It was unclear which pollutant each review was referring to. Any significant variation seen could thus correspond to variations in the device being reviewed rather than the pollutant.

The variation in the mean prevalence of different topics for the reviews associated with different devices is presented in Figure 5. Each device is referred to by its ASIN (Table 1). There appears to be significant variation in the prevalence of each topic by device.



Figure 5. The mean estimated proportion of words belonging to different topics (topic prevalence) from reviews corresponding to the different low-cost air quality monitors (referred to by ASINs).

4. Discussion

The analysis of the key themes discussed by users of low-cost sensors in the Amazon reviews of these devices represents a first step in understanding (1) the motivations of the public in purchasing these sensors and (2) how such the sensors are being used.

Specifically, this article found that many users have purchased devices to track wildfire smoke, manage health conditions such as allergies, evaluate specific sources of concern, and generally learn about air pollution in their environments. The use of low-cost sensors as a tool during smoke events was the most prevalent theme.

The identification of these uses can spur new ‘fitness-of-purpose’ tests of low-cost sensors for these purposes. For example, it is becoming increasingly evident that it is important to evaluate the performance of such devices to detect wildfire smoke as many users are making important decisions to protect their health during such events, such as deciding when to open their windows. Existing protocols, such as those used by the South Coast Air Quality Management District [26] to evaluate sensor performance typically do not include testing these devices during smoky conditions. However, important research is underway to evaluate different devices during wildfires and to develop adjustment factors for measurements from different low-cost sensors to improve their accuracy in capturing wildfire smoke [27,28].

From the variations in ratings of each product (std dev > 1 for greater than 90% of the devices) (Table 1), it appears that users of the same device can have very different experiences with the same product. This analysis found that users who reported using the device to track wildfires and manage allergies tended to be positive about their experience with the device. Reviews where topics related to the device operation, battery life, and concerns about the accuracy of the instrument were most prevalent tended to be associated with low ratings (Figure 4A). This is likely the case because different reviewers evaluated their devices very differently. Some found that their device allowed them to correspond

changes in the measurements of their device with that of smoke alerts and the feelings of well-being that allowed them to take necessary action. This correspondence perhaps allowed these customers to take for granted the accuracy of their devices for their purposes. Many such reviewers had become ‘attuned’ to their devices and provided details on how much time it took for their devices to respond to different sources. For example, two such example reviews were:

“...I tested (very informally) it [the device] by putting it near known pollutants and the response time was much quicker than expected (a couple to 10 s of being in the same area started it spiking up).”

“...I put it near a smoky area and also near the exhaust of my car. It takes a good 4 to 5 min before it starts to read “unhealthy levels.”

These reviewers used their devices for making decisions, such as when to turn on their air purifiers and take extra precautions to protect their health (Table 1). Others found that their devices did not correspond to the visual evidence of smoke alerts or did not detect known sources, which made them question the accuracy of their devices, explicitly bringing it up. Still others compared the readings of their devices with the EPA readings for their area/the nearest PurpleAir monitor. Many others took the accuracy of their devices for granted and used their devices to understand the air quality in their environments (Table 1). Crucially, only one review explicitly mentioned the formal regulatory evaluation of the product they were using. This suggests that the work regulators are doing to evaluate different sensors needs to be more widely disseminated. More information overall about the limitations of these low-cost sensors needs to be disseminated to the public as a whole, especially for the safety of users who were making key decisions solely on the basis of such devices.

Finally, IoT issues and ease of access to data were also key topics of discussion. Some reviews provided interesting information on the design features the customer found useful for interpreting the measurements from their device. Several reviewers discussed how being able to visualize trends over time allowed them to identify actions that they could avoid. Such insights could help scientists and regulators who work with communities to visualize and present data in a manner that is most helpful. For example, one reviewer wrote the following review:

“.....The device looks great and the display on the device itself is pretty easy to understand once you get used to what each of the bars means. I also like how the display can be adjusted to show any of the metrics individually or can be used as a simple clock if desired. I also appreciate the light level adjustment and the sleep mode which would come in handy if using the device in a bedroom. Additionally, I have found the mobile software to be top notch. I like being able to track trends over time and see the impact of my actions in graph form.”

There are several limitations with this approach. One: Although Amazon reviews are readily available, they do not capture the whole span of a user’s experience of using low-cost air quality sensors. In future research, in-depth interviews and surveys are required to build on this work. Two: Amazon reviewers of low-cost sensors are likely not representative of the general population using such devices. Some reviews may also be spurious (e.g., companies leaving bad reviews for their competitors and companies using third parties to self-promote their own product). Amazon has some protections in place to help limit the number of spurious reviews, such as by denoting a verified buyer. However, the themes identified still capture important topics discussed by close to 2000 users of low-cost devices. Three: We do not have any socioeconomic or demographic information on Amazon reviewers and therefore cannot detail how sensor usage patterns differ in different subpopulations. Recent research suggests that low-cost monitors tend to be deployed in more privileged neighborhoods [29]. It is important to conduct targeted research in the future to understand how to support the use of low-cost sensors by populations in less privileged neighborhoods who bear the brunt of air pollution. Four: Different pollutants

are produced by different sources and have different health effects. Because of the lack of information about the kind of pollutant being described in each review, this article was not able to generate separate topics of discussion for users concerned with different pollutants. Five: It is important to acknowledge that the interpretations and summaries of each topic identified by the topic model are subjective. This is a common limitation for topic modeling as the labeling of topics is often determined through examination of the most probable words, which are not necessarily exclusive to a topic and represent a small fraction of the probability distribution. Six: This analysis does not present an exhaustive list of the use cases of low-cost devices. It only serves to highlight key themes that the users brought up in their reviews of these devices.

Despite these limitations, this work represents the first effort to gain an in-depth understanding of how low-cost sensors are actually being used by the public and what users tend to want to know about the air pollution they breathe. These findings could support interventions designed to support such communities of users, as well as spur interviews to understand the different use cases of such devices in more detail.

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