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Toward Improved Safety Culture in Academic and Industrial Chemical Laboratories: An Assessment and Recommendation of Best Practices

Sopuruchukwu Ezenwa,[#] Abhijit D. Talpade,[#] Pushkar Ghanekar, Ravi Joshi, Jayachandran Devaraj, Fabio H. Ribeiro, and Ray Mentzer*

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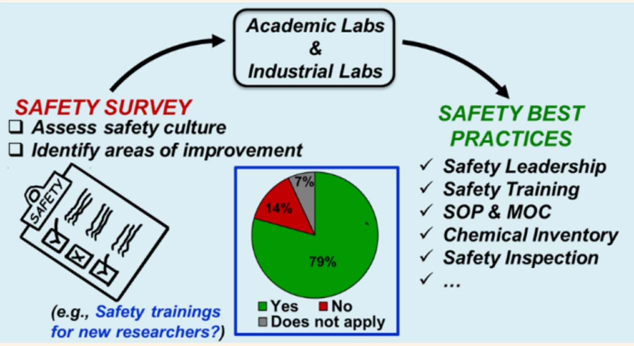

ABSTRACT: Numerous injuries and fatalities in chemical laboratories in the United States over the past few decades have suggested the need to take measures that go beyond mere compliance and toward promoting safer practices. A collaboration between the Center for Innovative and Strategic Transformation of Alkane Resources and Purdue Process Safety and Assurance Center assessed the current safety culture in chemical laboratories at their academic and industrial partners by conducting safety surveys. Key areas of improvement were identified from the responses to the safety surveys, which if addressed can mitigate the severity of safety incidents or prevent them from occurring. The findings indicate that a majority of the respondents from academia conduct comprehensive lab safety trainings (~80%), have standard operating procedures for potentially hazardous activities (~90%), regularly discuss safety-related issues during lab group meetings (~85%), or are involved in routine safety inspections (~85%). However, fewer of the academic respondents were aware of a database for safety incidents in their departments (~50%) or utilized a standard safety review process for new experimental setups or modifications to existing setups (~70%). The results from industry respondents suggest that improvements to commonly used hazard evaluation tools and increased accessibility to comprehensive databases can increase the effectiveness of hazard evaluation processes. Additionally, recommended best practices and guidelines are provided for researchers within the scientific community to develop key safety documentation that will both strengthen the safety culture and improve safety performance in their laboratories. Taken together, this safety initiative highlights the much-needed attention and effort that are beneficial to promote improved safety culture within academic and industrial chemical laboratories.

KEYWORDS: *safety culture, laboratory safety, safety survey, safety practices, best practices, hazard evaluation*

1. INTRODUCTION

Industrial and academic research facilities are the workhorses of most fundamental and applied scientific research. It is of utmost importance that those participating in research within these laboratory settings are safeguarded from the wide variety of hazards.[1−4] Safety incidents including near-misses and accidents that result in property damage, injuries, and fatalities have continued to occur in the laboratory setting at research facilities around the world, despite the fact that only a few of the more serious incidents have made it to the national news.[5,6] To that end, there have been concerted efforts to document these incidents, analyze their root causes, and ultimately propose measures to prevent or mitigate similar future incidents. Despite these efforts, the trend, as reported by the CSB, suggests that incidents are still prevalent. Figure 1 shows the summary of a data set from the CSB highlighting that the injuries and fatalities in laboratories have continued to occur in government and private sectors, in universities, and even in high schools.[7] There are still notable examples of recent lab safety incidents in 2018−2021.[5,8−11] These trends suggest a need for broad and systematic changes in laboratory practices that go beyond mere safety compliance and toward embracing safer practices and building a strong safety culture.[1−3,12−15] In other words, laboratories should exhibit a positive attitude and commitment toward safety among their members in a manner that takes precedence over other vital work functions and that fosters a work environment with reduced frequency of occurrence or

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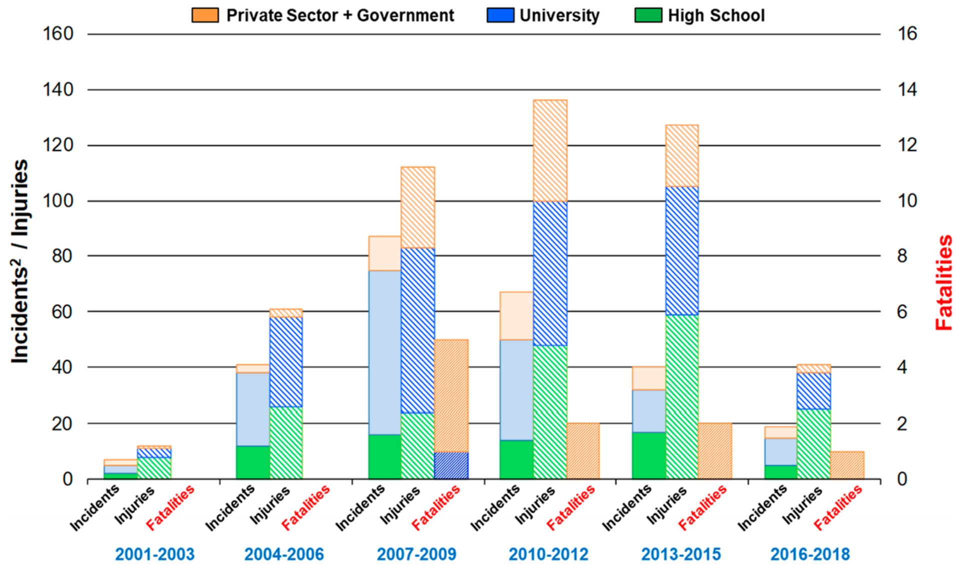

Figure 1. Summary of the number of reported incidents and injuries identified by the CSB in laboratories between January 2001 and July 2018 (adapted from ref 16, American Chemical Society, 2021).

severity of safety incidents. Thus, safety practices should not only be merely implemented but also improved upon based on the work requirements in the laboratory. In this work, the safety culture associated with an organization is defined as the attitude and behaviors of its members toward safety. A strong safety culture signifies the commitment of an organization and its members to safety as a priority to other vital organization goals to ensure protection of life, property, and environment.[1]

In the last several years, academic lab safety has evolved as an integral area of research and has garnered importance in the aspects of health and safety management. So far, laboratory safety culture and practices have been investigated via two methodologies: (1) an analysis[17−19] of previous safety research and past safety incidents pertaining to near-misses, injuries, and fatalities or (2) ad-hoc surveying[20−26] of safety culture through self-reported questionnaires. A recent review and analysis of academic lab safety by Ménard and Trant critically examined the state of academic lab safety through a multifaceted spectrum by looking at safety incidents and fatalities at universities based in Canada and United States.[19] They highlighted both the lack of a central database to develop experiential-based policies and the need to solve the issue of underdocumentation of lab safety incidents to limit future occurrences. In doing so, the scientific community can better understand the key factors that contribute to lab safety incidents. Ménard and Trant further noted barriers for unanimous acceptance of safety practices, as well as incentives and interventions that could help in overcoming these obstacles. On a different note, Gosavi et al. reflected on the lab safety incidents that occurred at Northwestern University's campus between 2010 and 2017 and outlined some key variables and concerns that relate to occurrence of lab safety incidents.[18] In particular, their study noted that effective research programs should not only meet the minimum safety standards required by regulatory bodies but also intentionally focus on the identification, elimination, control, or reduction of inherent hazards and risks. By analyzing the 8-year incident data, they identified the most common types of injuries, key demographic affected by the incidents, and the subsequent expenditure to address lab-associated injuries. Furthermore, drawing insights from their analysis, Gosavi et al. successfully launched a hand injury prevention initiative to reduce the occurrence of future incidents. Together, these analyses of past lab safety research and safety incidents have underscored the need for interventions that promote safer laboratory practices.[18,19]

In addition to analyses of past incidents, surveys have been conducted at leading research institutions to understand and document the safety culture at these facilities. Traditionally, these surveys have been limited to a particular research facility or extended to only academic research labs.[20,21] Schröder et al. conducted pioneering work in the area of lab safety surveys where they examined the laboratory safety culture through self-reported surveys that focused on understanding and comparing safety practices at academic, government, and industrial research facilities based in the United States.[22] Their survey questionnaire was structured to evaluate researchers' risk perception and to build an overall understanding of the prevalent lab safety culture. Furthermore, their study revealed that while general safety guidelines and protocols existed in a majority of these facilities, lab-specific implementation through leadership of the principal investigator (PI) or division head was lacking in more than half of the facilities.[22] Also, in many university and government laboratories, research seemed to take precedence over potential safety concerns. These may be attributed to differences in organization and funding structure, labor relations, and hiring practices across the three sectors.[22] In general, compared to industry labs, academic labs lacked strong safety culture and critical infrastructure required to adequately conduct safety evaluation of experimental setups. In conclusion of their study, Schröder et al. suggested a top-down approach in academic settings where department chairs play an active role in encouraging PIs to emphasize the importance of safety in their research groups.[22]

Following the results from Schröder et al., it remained unclear if the insights and conclusions about lab safety culture extend beyond United States-based research institutions. Ayi and Hon examined the apparent lower occurrence of major safety incidents in Canada compared to the United States.[23] Their pilot survey at a medium-sized Canadian university suggests that Canadian laboratories were also affected by poor risk assessment practices and inadequate knowledge on the use of personal

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protective equipment (PPE). Similarly, Leung[24] conducted a pilot study to probe the safety culture among laboratory workers (research students and technical staff) at two Hong Kong universities and compared the findings to the 2012 International Laboratory Safety Survey.[22,27,28] Overall, the results from Leung's study suggest that although safety priority among respondents seemed to be high when compared to the 2012 International Survey, certain related aspects, such as those relating to informal risk assessment and safety trainings, were limited. In essence, results from these various surveys[22−24] echoed similar findings that the current existing research laboratory safety infrastructure is inadequate globally and recommended that systematic measures, such as a top-down approach involving university management and independent safety councils, are needed to promote stronger laboratory safety culture.

This work builds upon the previous foundational work on the analysis and survey of safety practices. Using a survey, we assess current safety practices in industrial and academic labs affiliated with two multi-institution research centers (Center for Innovative and Strategic Transformation of Alkane Resources (CISTAR) and Purdue Process Safety and Assurance Center (P2SAC)). This survey was motivated by the need to generate focused insights considering the safety culture at a much more local scale, which may otherwise be hidden by larger-scale nationwide surveys. Furthermore, the survey seeks to understand the safety culture in industrial and academic research laboratories and aims to facilitate sharing of best practices between them. From the results of the survey, we highlight both key findings and areas of improvement and further provide best practices and guidelines for developing safety documentation that may be useful for members of the broader community to assess and strengthen safety culture in their respective settings. Finally, the learnings from this survey also contributed to the planning and development of an online tool to support preliminary hazard and safety analysis.[16,29] This tool called Reactive Hazard Evaluation & Analysis Compilation Tool (RHEACT) provides a convenient platform for researchers to compile, analyze, and prioritize hazard-related information when planning laboratory experiments.[16]

2. METHODS

This study involved two surveys in which one focused on academic research laboratories and the other focused on industrial research and development (R&D) laboratories. Both surveys were administered in 2019−2020, and the authors of this study developed the survey questions. The study was designed to obtain a maximum of one response per academic lab or industry organization. To ensure this, the surveys were distributed directly to laboratory PIs and to one representative per industrial organization. Although anyone in the academic or industrial lab could fill out the survey, we specified that we were seeking a maximum of one response per academic lab or industry organization. Here, we assume that there was a maximum of one PI per academic lab and that at most one representative responded per industry organization. Because of the option for anonymous responses, we could not fully verify if these assumptions hold. However, we can confirm that all the nonanonymous responses (11 for academia and 15 for industry) were from different academic labs or industrial organizations. In addition, the surveys were approved by the Purdue Institutional Review Board. All data collection, analysis, and storage were performed in accordance with relevant guidelines and regulations.

2.1. Participant Selection and Survey Distribution. The scope of the survey was limited to chemical research laboratories at CISTAR and P2SAC academic and industrial partner institutions.[30,31] The academic lab safety survey was distributed online via Qualtrics to about 150 chemical engineering and chemistry research laboratory PIs at the five CISTAR partner universities. Out of these, 31 responses were received. On the other hand, the industrial lab safety survey was distributed both in printed form (to industry representatives who attended the P2SAC Spring 2019 conference) and in online Qualtrics form to about 60 P2SAC and CISTAR industrial partners. From the distributed industrial lab safety survey, 26 complete responses were received. Based on their survey response, 10 participants were contacted for follow-up discussions, and five of them interacted with the survey team via email and video discussions. For this study, the unit of analysis was either a laboratory group for the academic survey or an industrial organization for the industrial survey. No incentives were provided for survey participation.

2.2. Questionnaire Design and Measures. The academic and industrial lab safety surveys were self-reported and designed to be completed in 10−20 min by participants. A sample of both surveys can be found in the Supporting Information. Participants had the option to respond anonymously. The specific identities of nonanonymous respondents were stored in a secured database only accessible to the survey team for purposes limited to follow-up discussions, and the information remains confidential.

The academic lab safety survey was designed to develop quantitative metrics to evaluate the current safety practices at the academic research labs, identify areas for improvement, and compile best practices. Most of the questions in the academic lab safety survey were delivered in close-ended questions (predefined answer options). The close-ended questions included dichotomous questions ("Yes" or "No"), multiple choice questions with one-response needed, multiple choice questions with more than one response ("Select all that apply)," and rating scale questions. In some of these questions, additional options such as "Not sure," "Does not apply", or "Other" were provided. Furthermore, respondents were asked specific follow-up open-ended questions depending on the choices that they made in the parent question. All survey questions can be found in the Supporting Information. Not including the demographic section, the academic survey was presented in the 10 dimensions (maximum of 45 questions). The maximum number of questions per dimension depended on the specific responses to parent questions by the respondents. We summarize these as dimension (minimum number of questions per dimension and maximum number of questions per dimension): Lab-specific safety training (1, 6); review process for a new or existing experimental setup (1,4); safety-related discussions during lab meetings (1,4); communication of safety incidents in department (1,6); use of standard operating procedures (1,3); chemical inventory management (1,2); safety leadership (2, 5); safety inspections (2,6); special safety initiatives (1,3); department-specific safety training (2,3); and special safety trainings (3, 3).

On the other hand, the industrial lab safety survey was aimed to assess the safety practices in industrial R&D labs/pilot plants, understand their hazard evaluation processes, and obtain helpful insights for the development of a hazard evaluation tool.[16] 8 out

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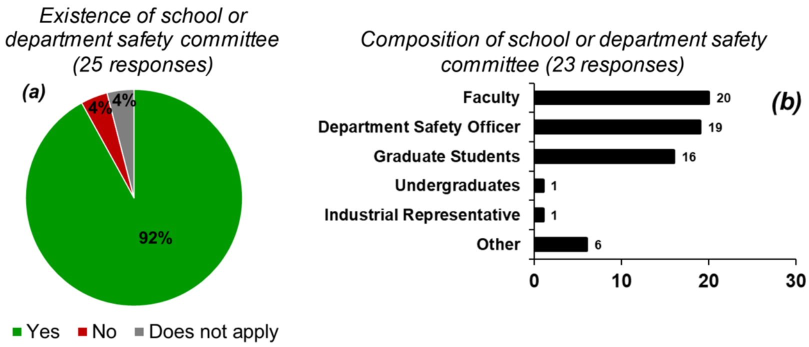

Figure 2. Participants' responses to questions about (a) existence of the safety committee and (b) composition of the safety committee at the department level.

of 10 questions were open-ended; the remaining two questions were close-ended questions on software tools and databases used for hazard evaluation.

2.3. Analysis. For analysis, the questions in the academic lab safety survey were regrouped into the following four subcategories: (i) demographics of respondents, (ii) lab safety leadership and safety training, (iii) safety documentation for new or modified procedures/materials/setups, and (iv) initiatives to promote stronger safety culture. The industrial lab safety survey was grouped into five categories: (i) data collected for hazard evaluation, (ii) tools and databases used for hazard evaluation, (iii) hazards evaluated, (iv) desired improvements to the hazard evaluation process, and (v) initiatives used to develop stronger safety culture. The industrial survey responses were analyzed for similarities in the responses for the data collected and tools/databases used for hazard evaluation to identify the standard hazard evaluation procedures. Furthermore, the results of the open-ended questions are presented as aggregates of all the responses.

Major trends were identified by analyzing the responses from the academic lab safety survey (n = 31) and the industrial lab safety survey (n = 26), and simple summary statistics were used to communicate these key trends. Data analytics was performed with the aid of Qualtrics and Microsoft Excel tools. Because of the limited scope of this study at CISTAR and P2SAC partner institutions, the sample size is relatively smaller than some previous studies.[21,22] Thus, this work is limited to exploratory data analysis that provides both high-level quantitative and qualitative insights into lab safety practices at the surveyed institutions. Detailed quantitative analyses and statistical significance tests were not performed on the current data set, and any conclusions inferred are not necessarily generalizable beyond the current scope of this study. However, observed trends may provide insights into some of the current practices in academic and industrial research laboratories.

3. RESULTS AND DISCUSSION

This work relies on a few assumptions to both quantitatively and qualitatively identify highlights within the scope. The survey was sent to individual PIs or industry representatives at CISTAR and P2SAC partner institutions, and it is assumed that there was a maximum of one response per academic lab or company. Also, the respondents were assumed to be knowledgeable of most of the general lab safety practices in their groups or organization. The relatively smaller sample size and the voluntary nature of the survey may create a nonresponse bias in which responses are mostly composed of respondents who are more safety conscious than the average target population.[32,33] Also, the use of self-reported data from safety surveys has been identified to include some social desirability bias that suggests that responses may be given in a manner that is viewed favorably by others.[19,34]

3.1. Academic Lab Safety Survey. *3.1.1. Demographics of Respondents.* The respondents (n = 31) to the academic lab safety survey took an average of 27 min to complete the survey. Of the 31 responses, 26 were full responses while five were partial responses. The partial responses were identified as the ones with less than 20% completion of the minimum number of survey questions. One duplicate response was also received. Incomplete and duplicate responses were not included in the analysis. Nearly one-third of the respondents (11) completed the survey nonanonymously while the others (20) provided responses anonymously. Slightly over half (55%) of the respondents have more than 10 years of experience working in a research laboratory setting. Most respondents (90%) had more than 4 years of experience working in a lab setting. None of the respondents had less than a year of experience. Nearly all respondents with 10 or more years of experience (17) were also identified as PI/faculty. The other respondents included graduate students, lab safety officers/managers, staff researchers, and postdoctoral scholars.

3.1.2. Safety Leadership and Safety Trainings. A safety leader is an individual who oversees and ensures compliance of a laboratory safety program. They can exist at levels of individual research group, department, or institution and could include graduate students, postdoctoral researchers, laboratory PI, departmental safety director, and department chairperson.[35−37] From the survey responses, 21 out of 24 respondents identified that they had an internal student safety leader (e.g., safety officer) who takes ownership of administrative/review aspects of safety in their research group. In addition, 85% of these respondents noted that the responsibilities of the safety officer were documented to ensure smooth transitions and accountability. As Schröder et al. pointed out in their work, a top-down approach with the active involvement of the PIs, departmental chairs, and the management for laboratory safety activities is important.[22] It is not only the responsibility of the safety leadership team (safety office and PIs), but also the responsibility of every laboratory member to take the required steps to ensure a safe working environment in the laboratory. Figure 2a shows statistics on the existence of a safety leadership entity, and Figure 2b shows the composition of such entities. At the department level, 23 out of 25 respondents were aware that their departments have a safety committee (Figure 2a). For the respondents (23), the committee is composed of predominantly faculty (20), department safety officers (19), and graduate

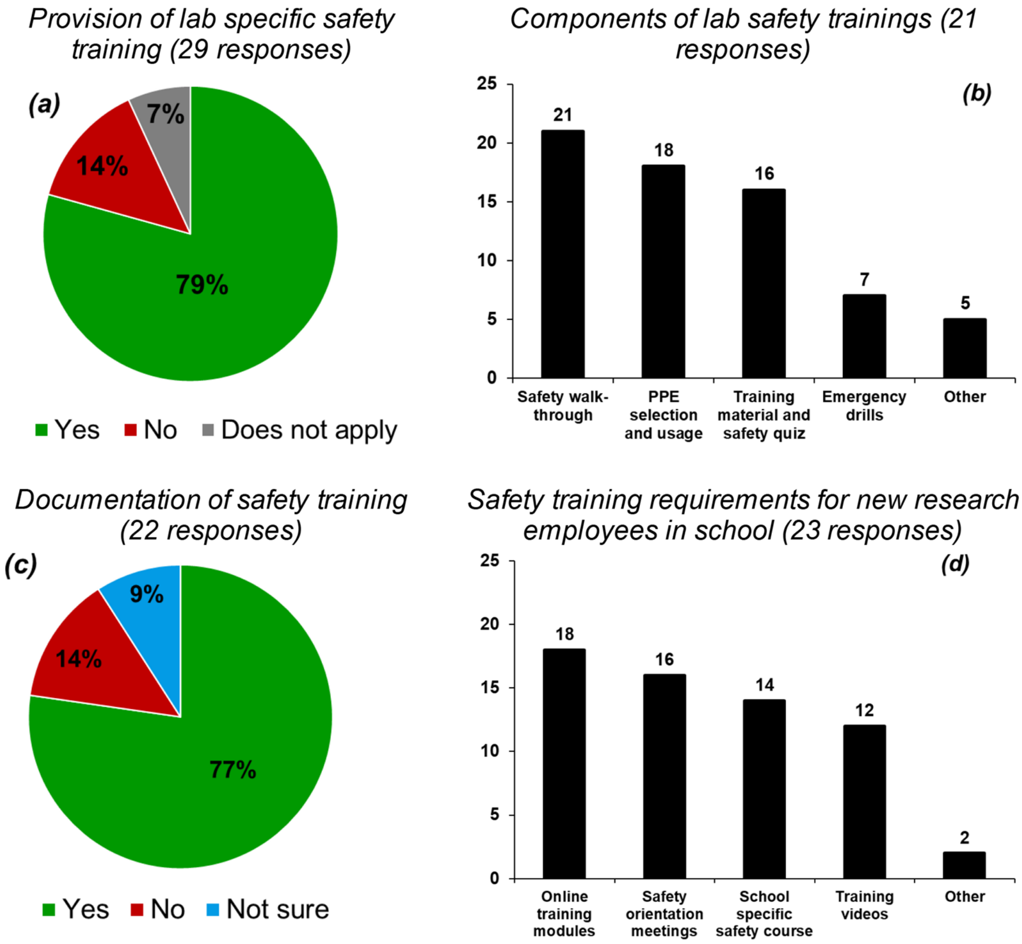

Figure 3. Statistics on safety training: (a) provision for lab-specific safety training, (b) components of lab safety training, (c) documentation of lab safety training, and (d) safety training requirements for new research employees in school.

students (16), and in rare cases, the committee is composed of undergraduates or industrial representatives (Figure 2b). Furthermore, 87% of the same respondents were aware that their department safety committee provides guidelines to ensure consistency in safety expectations and training across different research groups.

Survey respondents were asked several questions related to the lab safety training, and the results are summarized in Figure 3a–d. About 79% indicated that lab-specific safety training was offered in their lab for new researchers, while 14% indicated that no lab-specific safety training was offered in their lab/group (Figure 3a). Previous studies on lab safety practices by Schröder et al. reported that about 70% of the academic respondents (n = 991) of their lab safety survey received training before they could carry out an experiment.[22] In our survey, among those (23) who indicated that lab-specific safety training was offered, the majority of them (18) noted that an assigned group safety officer provides the safety training. The PI and fellow group members were also identified to provide lab safety training by less than three respondents. Given the fact that more than half of the survey respondents were PIs, these results suggest that the lab safety training is predominantly the responsibility of a group safety officer, presumably appointed by the PI. In addition, Figure 3b shows that lab-specific training is limited to mostly safety walkthroughs, PPE selection and usage, and training material with safety quizzes. About 75% of respondents indicated that different measures such as documentation and checklists were put in place to ensure consistency of the lab-specific safety training. Similarly, about 77% of respondents were aware of the documentation and maintenance of individual researchers' safety records (Figure 3c). Also, as shown in Figure 3d, more than half of the 23 respondents indicated that safety training requirements for new research employees at their school include online training modules, safety orientation meetings, school-specific safety courses, or training videos. Furthermore, competency ensured through certifications on completion of safety trainings and graded quizzes was associated with slightly more than half of the respondents (57%), while only certifications with no graded assessments were required in 38% of the responding labs.

Regarding special training sessions for lab personnel, more than half of the 23 respondents indicated that their department offered training sessions on use of fire extinguishers (18 respondents), working with hazardous chemicals (11 respondents), cardiopulmonary resuscitation (eight respondents), and first-aid (four respondents). Furthermore, more than half of the respondents were aware that their institutions offer other specialized training related to individual needs such as working with radiation, blood pathogens, laser, electricity, and respirators. Finally, out of 22 respondents, the majority (73%) were not sure that their department has training programs for nonlaboratory personnel (e.g., custodians) who might routinely need to enter laboratories to perform their duties.

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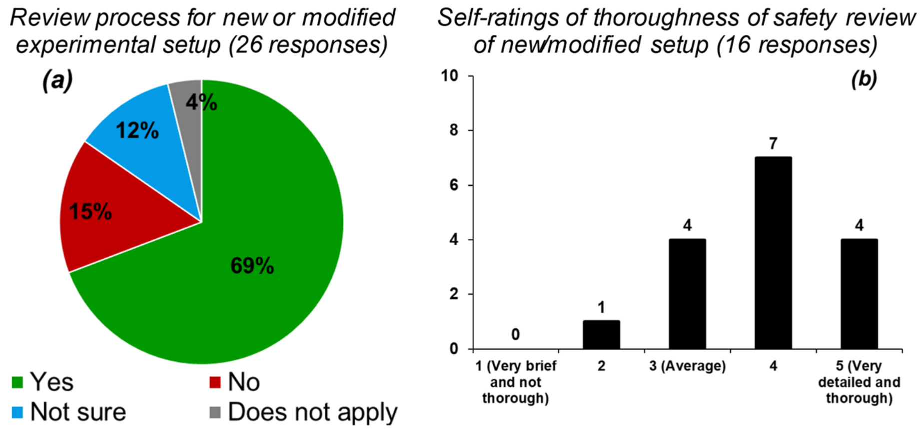

Figure 4. Responses to academic lab safety survey questions on (a) existence of review process for the new or modified experimental setup and (b) self-ratings on thoroughness of the safety review of the new or modified experimental setup.

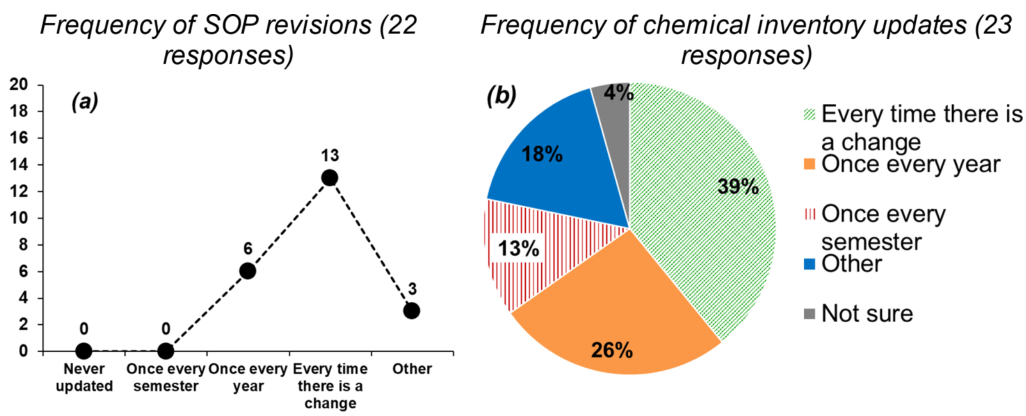

Figure 5. Responses to frequency of updates of (a) SOPs and (b) chemical inventory.

Taken together, this academic lab safety survey has identified that most (>90%), but not all of the respondents, were aware of a safety leadership structure in their groups and department. However, about one in five respondents were unaware of either the provision of lab-specific safety training to new lab personnel or the documentation of lab personnel safety trainings.

3.1.3. Safety Documentation for New or Existing Procedures. Researchers often need to install new experimental setups or modify existing apparatus or protocols for new experiments. Safety incidents have often occurred in the research lab because of inadequate risk assessments, and prior surveys have called attention to these deficiencies.[7,18,21−23,38] Considering this, the survey included questions to gather information on different aspects related to safety documentation for new or modified research procedures. Responses to questions about the existence and self-evaluation of safety reviews for experimental procedures are shown in Figure 4a,b. From Figure 4a, 69% of 26 respondents identified that there was a review process for new or modified experimental procedures (e.g., management of change (MOC) procedure). More than half of the respondents that noted the existence of a review process indicated that this review process involved the lab PI, safety officer, peers, or the researcher who made the modifications. A respondent (a lab PI) noted that after the review is sent to them by the student for approval, time will be devoted at the start of a group meeting to discuss the new procedures and inform as well as obtain input from all lab members. Furthermore, when asked to rate the thoroughness of the overall safety review of a new or modified experimental setup, the average rating of the 16 respondents was 3.9/5.0, which translated to a detailed and thorough review (Figure 4b).

The participants were also asked about documentation for existing research procedures and research paraphernalia. Most of the respondents (23 out of 25) indicated that standard operating procedures (SOPs) were available for critical laboratory equipment and recognized hazardous activities within their research group or department. Figure 5a,b summarizes responses to questions about frequency of updates of SOPs and chemical inventory. These respondents also identified that these critical/important SOPs were updated at various frequencies ranging from once every year to every time a change is made (Figure 5a). Most of the respondents also identified that these SOPs were made available to users in various formats ranging from printed copies next to equipment to a virtual copy maintained on an easily accessible network drive. Regarding documentation of chemicals used or stored in the laboratory, 23 out of 24 respondents identified that they had a procedure in place to keep track of these chemicals. However, the chemical inventory was updated at various frequencies ranging from once a year to whenever a change was made (Figure 5b). In addition, 72% of respondents were aware that their university has a formal program such as a Chemical Hygiene Plan to ensure health and safety of all employees working with hazardous chemicals in a laboratory setting.

Overall, most respondents (∼93%) maintained key safety documentation (e.g., SOPs and chemical inventories) for

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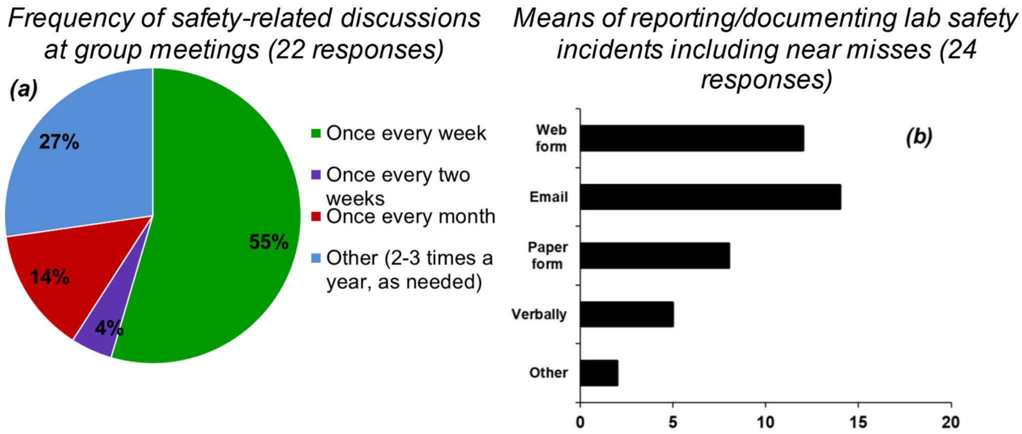

Figure 6. Responses to questions about (a) frequency of safety-related discussions during group meetings and (b) means of reporting or documenting safety incidents and near misses.

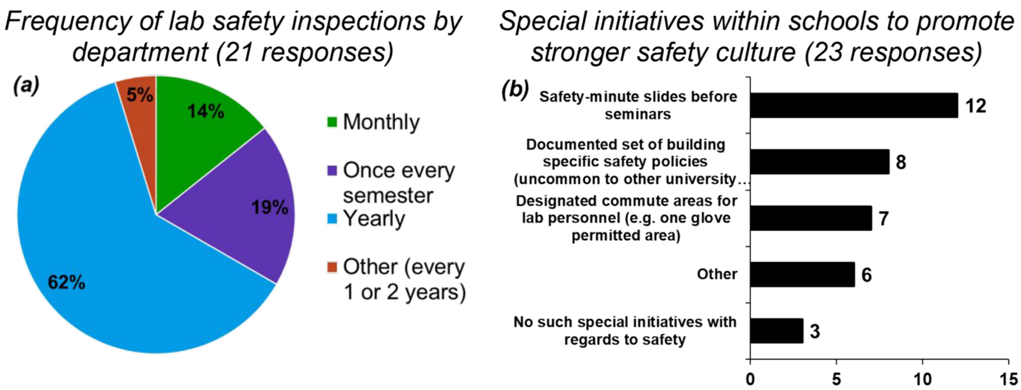

Figure 7. Responses to (a) frequency of lab safety inspections by the department safety committee and (b) special initiatives within schools to promote stronger safety culture.

existing critical and potentially hazardous research procedures and chemicals. However, 30% of respondents were unaware of a review process for new or modified research procedures, while the other 70% gave an average rating of 3.9/5.0 on the thoroughness of the overall safety review in their group.

3.1.4. Initiatives and Measures to Promote Stronger Safety Culture. Because research laboratories are inherently dangerous work environments, a poor safety culture has been previously implicated as one of the root causes of various safety incidents.[3,19,23,39] A stronger safety culture (a more conscious and positive attitude toward laboratory safety) is indicated by actions that go beyond meeting the minimum requirements for compliance. To assess the safety culture in research labs, respondents were asked questions about safety initiatives in their research group, and responses to some of the questions are summarized in Figure 6a,b. Majority (85%) of respondents (26) indicated that their research group conducts safety-related discussions during group meetings, albeit at various frequencies (Figure 6a). In addition, 19 out of 22 respondents indicated that external safety incidents (from other academic or industrial labs) were either sometimes (seven respondents) or regularly (12 respondents) talked about during group meetings. Respondents also noted that other topics such as safety tips, PPE changes, lone worker policies, near misses, or other topics of concern were routinely discussed.

Because lab safety culture can sometimes be a reflection of department or institution safety culture,[12,37,40] respondents were asked questions about safety initiatives at the department or university level. For example, a formal system to report and document near-misses is important to catch early signs/warnings or gauge the effectiveness of the safety program in place and continue to drive a strong safety culture.[37,41] About 92% of 26 respondents are familiar with a formal system to report safety incidents including near-misses to the department or university. These lab safety incidents were to be reported or documented via various means (Figure 6b) including web forms, emails, paper forms, or verbal communication.

Internal documentation of lab safety incidents, including near-misses, has limited use if these incidents are not communicated to the local or broader research community,[41] because transparency breeds a stronger safety culture. About 18 out of 24 respondents were aware that incidents and recommendations to prevent similar situations were circulated within their department, and most of these communications were done via email (16 respondents) or posters (three respondents). However, among 24 respondents, 50% were not sure if a database of safety incidents is maintained by their department and 42% were aware of such a database, while 8% indicated that no such databases exist.

Although various safety initiatives are strongly suggested but not usually mandated, measures are needed to ensure that the highest safety standards are attained. Compliance checks such as safety inspections serve the purpose of reinforcing minimum safety standards at academic research labs. Out of 24 respondents, 13 indicated that their department conducted safety inspections of both lab and office spaces, eight indicated

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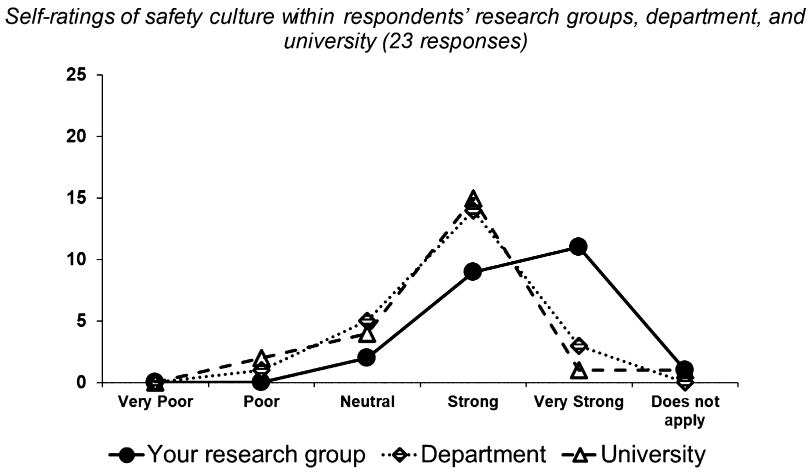

Figure 8. Respondents' self-reported evaluation of the safety culture within their group, departments, and university.

that only lab spaces were inspected, and three respondents indicated that no safety inspections of lab and office spaces were conducted. In addition, as shown in Figure 7a, the frequency of safety inspections varied from every month to every 2 years. Furthermore, 19 out of 21 respondents reported that these safety inspections were announced, while 12 out of 21 respondents identified that unannounced safety inspections also occurred. Some of the respondents also noted that various follow-up processes were put in place to ensure that violations and deficiencies are addressed in a timely manner. In addition, 21 out of 25 respondents indicated that the health and safety department at the university level periodically inspects laboratories each semester (four respondents) or once every year (16 respondents). As summarized in Figure 7b, various special initiatives at the school level were also identified by respondents to promote safety awareness and incubate a stronger safety culture. Furthermore, respondents mentioned that the most effective safety initiatives in their group or school included regular safety discussions in research group meetings, safety officer ensuring compliance, mandatory safety trainings, and unannounced safety inspections and audits.

Finally, respondents were asked of their perception of the safety culture in their research group, department, and university, and the responses are shown in Figure 8. We observe that most respondents think that the safety culture in their research group is stronger than that in their department or university. This perception may suggest that the individual research groups surveyed maintain safety standards that go beyond the minimum safety standards set by their departments or universities.

3.2. Industrial Lab Safety Survey. The industrial lab safety survey was circulated to the industry partners associated with CISTAR and P2SAC.[30,31] These multinational companies bring decades of heritage and a dedicated safety culture. The purpose of the safety survey was to understand the current best practices for hazard analysis employed by the industrial laboratories, with specific focus on hazard data collection/generation, identification, documentation, and safety training. The findings from this survey could also benefit the small- and medium-sized enterprises (SMEs) and the academic laboratories in developing safety practices for their research laboratories.

3.2.1. Demographics of Respondents. A total of 26 complete survey responses were collected from representatives of companies that could be classified in one of the following sectors: pharmaceuticals, chemicals, oil & gas, engineering, polymers, petrochemicals, and energy. About 16 of the 26 identified respondents belonged in the following categories: process safety group members, technical R&D group members, or leaders of process safety and technical R&D groups. No differences were identified between the respondents who received the survey and those who did not respond. From the 26 complete responses, 15 responded nonanonymously while the rest remained anonymous. The survey team also reached out to 10 survey respondents with follow-up questions via email and video interviews to gain additional insights into laboratory safety practices and safety documentation. Of these, five provided additional insights.

3.2.2. Data for Hazard Identification. Most of the companies participating in the industry safety survey self-reported that they collected some or all of the following data for their hazard analysis procedure:

(a) Thermal stability data: using differential scanning calorimetry or accelerating rate calorimetry data.
(b) Individual chemical hazard data: flammability, toxicity, and reactivity data.
(c) Physical and chemical properties of the individual chemicals.
(d) Chemical compatibility data: between the participating reactants and products and with the material of construction of the equipment.
(e) Heat of reaction data.
(f) Expected operating conditions (temperature, pressure, and flow) along with pressure generation potential/temperature change calculations.

A few responses included additional data collection on the scale of reaction (reaction volume) and equipment design parameters like layout, relief devices, and safety interlocks.

3.2.3. Tools and Databases Used for Hazard Evaluation. The survey responses highlighted the use of specific online tools and databases for the purpose of data collection during hazard analysis. Among the online tools, the most used tools included CAMEO Chemicals or chemical reactivity worksheet (CRW), which is used for performing a chemical compatibility analysis of the chemicals involved in the reaction system (analysis based on the reactive functional group analysis) and CHETAH for studying the chemical reactivity and for evaluating the heat of reaction data. A few responses also mentioned the use of electronic notebooks and in-house developed tools for data

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collection. In the case of data collection, safety data sheet (SDS) databases, Bretherick's Handbook of Chemical Hazards, Scifinder, and Web of Science were the sources used predominantly. About 32% of the respondents reported that they use proprietary tools and about 58% of the responders reported that they mainly used in-house developed tools and databases for data collection (Figure 9).

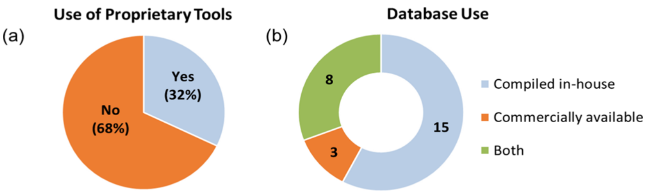

Figure 9. Online tools/databases used for data collection during hazard evaluation in industrial laboratories.

3.2.4. Hazards Evaluated. The data collected using the online tools and/or databases were used to evaluate several process hazards. The industrial lab safety survey respondents mentioned the use of the data mentioned in Section 3.2.2 to evaluate the gas generation potential, chemical reactivity, and exposure hazards. Apart from these, a few responses highlighted evaluation of additional hazards based on the scale of the reaction employed (reaction volume), identification of potential ignition sources, and PPE requirements.

3.2.5. Building an Effective Hazard Evaluation System. Along with hazard identification and evaluation, the industrial lab safety survey also aimed to understand areas of improvement in the current hazard evaluation processes and seek input on an effective hazard evaluation system. Based on the survey responses, automation of the process hazard analysis procedure (for example, development of an online tool that provides templates for the safety checklist, hazard operability study, or MOC procedures can help automate the process hazard analysis procedure) was identified to be one of the most common desired features of an effective hazard evaluation system. Other desired features included provision of a checklist for performing the prestartup safety review (PSSR), awareness of potential hazards, and guidelines for a safety review. Apart from these, a few survey respondents suggested a need for better data aggregation tools, that is, a single source for identifying all the data (physical, chemical, and reactive hazard data) associated with experiments, guidelines for PPE, chemical compatibility predictions, and chemical storage suggestions.

3.2.6. Safety Initiatives Employed. Effective communication of safety incidents including near-misses and periodic reinforcement of safety procedures are a critical and integral part of an effective safety program. The survey revealed that the participant organizations use a variety of tools to fulfill this. For example, many of the respondents use a standardized experimental review procedure and an effective action-item tracking system. Reporting near-misses and other safety incidents, regular safety updates via different channels (weekly bulletins, emails, reports, and meetings), safety audits, safety signages, and refresher courses have all been used to further strengthen their safety culture. These respondents also cited that the safety training consisted of both online and offline components involving computer-based training modules, operating procedures studies, and instructor-led trainings. The impact of near-miss reporting on improving laboratory and industrial safety has been addressed before.[41−47] Positive collaboration between the laboratory members and management can lead to the development of useful near-miss reporting tools and training modules that can help reduce/prevent safety incidents. Such tools should be adapted/developed by the laboratories for efficient safety communications. Similarly, self-reporting near misses through journal articles, open forums, and discussing the framework required for near-miss reporting analysis and implementation would prove to be helpful to the scientific community in implementing laboratory safety reforms.[44,48,49]

Furthermore, the inputs from the survey responses aided the compilation of key best practices for laboratory operations that are described in Section 3.3. A detailed outline for key safety documentation has also been developed by conducting additional follow-up sessions with a few survey respondents (see the Supporting Information).

3.3. Key Areas of Improvement Identified during Survey and Recommended Best Practices. Based on the results of the lab safety surveys, some key areas of improvement were identified. As stated before, there are identifiable differences in operation and management of laboratories in the industrial, government, and academic sectors. Keeping that in mind, the authors have compiled the list below, using insights developed from this study, as well as from other past studies,[20−24,35,36,50,51] for promoting a stronger lab safety culture. The authors understand that the implementation of some of the practices could be scale-dependent (for example, use of expensive hazard evaluation and safety database management tools), but important to improving/maintaining the safety of a laboratory. Specific guidelines and best practices are further discussed in the Supporting Information.

i. Safety leadership should exist within the research group and departments to oversee consistency in safety training and expectations.[35,36] An internal safety leadership position, preferably by a researcher who spends more time physically in the lab, has the potential to not only ensure compliance but also inspire initiatives that promote stronger safety culture.

ii. Lab safety training should be offered to new researchers and documented in a consistent manner by well-trained personnel.[52] Documentation helps to identify when refresher trainings are needed. Furthermore, departments are also suggested to periodically make researchers more aware of special safety training (based on individual needs) that researchers could potentially benefit from.[53]

iii. Standard operating procedures for potentially hazardous protocols should be available, accessible, and regularly updated. The regular implementation of SOPs and MOCs can ensure that there is consistency in the way that an experimental protocol was originally designed and prevent incidents that arise from deviations in the original protocols.[54]

iv. There should be a thorough review process for new or modified experimental setups which involves key lab safety leadership and appropriate documentation. Researchers are encouraged to implement some form of risk assessment and hazard evaluation for new or modified experimental protocols.[16,55−61] To supplement traditional methods for hazard evaluation and risk assessment, researchers may consider layer of protection analysis[62,63] to make informed decisions on adequacy of existing layers of protection during an imagined incident scenario.

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v. Group meetings should include regular safety-related discussions including discussions on recent lab/school/external safety incidents and learnings.[64]

vi. Chemicals should be properly tracked using a frequently updated chemical inventory. Improvements are needed in the frequency at which the chemical inventory is reviewed and updated.[51] This is important as some chemicals, such as peroxide formers, may become unstable when stored for a time longer than their shelf life.[65] Researchers should also ensure that chemicals are properly stored and segregated according to recommended practices.[66]

vii. Regular safety inspections should be carried out and deficiencies addressed in a timely manner.[67]

viii. A formal and easily accessible system for reporting and documenting safety incidents should be instituted to communicate safety incidents including near-misses. A formal system to report and disseminate lab safety incidents including near misses has been shown to have a positive effect on safety culture.[41−45,47,59] Communication of safety incidents and recommendations to the broader research community also serve as effective methods to ensure that these incidents are prevented in other research groups and thus should be continually encouraged.[10,11,18,41,48,49,68−71]

ix. Special initiatives and new training opportunities should be encouraged to re-enforce the safety culture, and they should be continually implemented at all levels from the research group level to the university level and beyond. These safety initiatives serve not only to ensure mere compliance in lab safety practices, but also to promote stronger lab safety culture.[72] The Research Safety Student Initiative[73,74] at Northwestern University (and similar graduate student-led safety teams at other universities[75−78]) and the Dow Lab Safety Academy[79,80] are examples of many such initiatives. Furthermore, an academia-industry partnership has been reported to mutually enhance the safety culture of all parties involved.[81]

4. CONCLUSIONS AND FUTURE OUTLOOK

This study provides insights into the current laboratory safety practices at the CISTAR and P2SAC partner academic and industrial institutions. The academic lab survey results provided both qualitative and quantitative insights into key topics such as lab safety leadership and safety training, safety documentation for new or modified procedures/materials/experimental setups, and initiatives to promote a stronger safety culture. On the other hand, the industrial R&D lab survey results provided information on hazards evaluated, hazard evaluation procedure used, desired improvements to hazard evaluation process, and safety initiatives used to develop stronger safety culture. On that front, a variety of hazard evaluation tools such as CHETAH, CAMEO, CRW, and RAST, widely used in industry, provide necessary methods to conduct hazard analysis. Similarly, based on the survey responses outlined in this report, our team has built an online tool[16,29] called RHEACT. This online open-source tool provides a convenient platform to compile, document, and assess hazard-related information before running experiments. It can parse multiple SDSs for chemical and safety information and generate an operational hazard matrix, compatibility analysis, and estimate adiabatic temperature changes. This tool aims to both make hazard evaluation more approachable and empower researchers to prioritize safety concerns.

We surmise that the results from this survey could help faculty and other research personnel to understand the blind-spots in the safety culture in their research groups and to find potential tools that could be adopted for improving the safety culture. In addition, because of the limited scope of this study, our results do not necessarily address all the unique hazards that may exist in academic and industrial labs in the United States. In the future, such a survey could be extended to other academic and industrial research laboratories (current survey includes only large-scale academic and industrial institutions but can be extended to small community colleges and SMEs in the future) to further generalize the trends observed for laboratory safety practices, identify areas of improvement, and provide recommendations for the best laboratory safety practices. Promoting safer laboratory practices (among lab researchers at all levels) has become the need of the hour as laboratory safety incidents are still prevalent. Therefore, implementing formal procedures for laboratory safety training, recognizing the importance of safety documents (such as standard operating procedures and MOC documents), and/or reinforcing a laboratory safety course as a part of the curriculum can help in improving the safety outlook of the future laboratory personnel and significantly reduce injuries/fatalities in the chemical R&D institutions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.chas.1c00064.

Detailed guidelines and templates for developing safety documentation (safety reviews, lab hazard analysis reports, SOPs, MOC, etc.) and industrial and academic lab safety survey questions (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Ray Mentzer − *Charles D. Davidson School of Chemical Engineering, Purdue University, West Lafayette, Indiana 47907, United States; Purdue Process Safety and Assurance Center (P2SAC), West Lafayette, Indiana 47907, United States;* orcid.org/0000-0002-7108-9175; Email: rmentzer@purdue.edu

Authors

Sopuruchukwu Ezenwa − *Charles D. Davidson School of Chemical Engineering, Purdue University, West Lafayette, Indiana 47907, United States*

Abhijit D. Talpade − *Charles D. Davidson School of Chemical Engineering, Purdue University, West Lafayette, Indiana 47907, United States*

Pushkar Ghanekar − *Charles D. Davidson School of Chemical Engineering, Purdue University, West Lafayette, Indiana 47907, United States*

Ravi Joshi − *Charles D. Davidson School of Chemical Engineering, Purdue University, West Lafayette, Indiana 47907, United States;* orcid.org/0000-0002-7820-3591

Jayachandran Devaraj − *Corteva Agriscience, Indianapolis, Indiana 46268, United States*

Fabio H. Ribeiro − *Charles D. Davidson School of Chemical Engineering, Purdue University, West Lafayette, Indiana 47907, United States*

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Author Contributions

[#]S.E. and A.D.T. contributed equally to this work. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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