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Enhancing Compliance and Process Monitoring in Engineering Labs with IoT-Driven RFID Solutions

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ABSTRACT

Inadequate or faulty test equipment and machinery in engineering laboratories pose significant safety risks and hinder both teaching and learning experiences. This compromises compliance with educational standards and quality assurance. As technological advancements continue to reshape laboratory management, there is a growing demand for increased transparency and trust from both regulators and stakeholders. An IoT-enabled RFID-based system can significantly improve compliance management in engineering labs, moving away from error-prone manual documentation processes. This study presents an automated compliance management system driven by RFID technology, designed to track and monitor three key compliance processes: maintenance, calibration, and asset status (e.g., outdated equipment). The system operates at frequencies between 902 MHz and features an integrated graphical user interface (GUI) that displays the real-time compliance status of equipment. Compliance is visually indicated using a color-coded system: green for compliant, yellow for near non-compliance, and red for non-compliance. The system also generates diagnostic reports for enhanced tracking and recordkeeping. Additionally, the system sends email notifications to supervisors when equipment approaches non-compliance thresholds, ensuring timely corrective actions. For example, as the compliance status approaches 180 days since the last service, the system shifts from green to yellow, signaling a minor issue. When the status reaches 90 days, the indicator turns red, marking a critical non-compliance. This proactive approach to compliance management, powered by RFID and IoT technologies, offers significant potential for improving operational efficiency and supporting long-term strategic planning in engineering laboratories.

Keywords: Engineering laboratory; process management; IoT enabled RFID technology; graphical user interface; compliance status

INTRODUCTION

Students have always been an integral part of the higher engineering education system and viewed as the primary recipients of the services offered by its engineering laboratory facilities. These service-oriented laboratory facilities are expected to be adequately equipped in terms of non-defective and non-substandard equipment and machinery as well as effectively maintained under a routine facility process. This is viewed imperative as laboratory facilities are highly used to expose student engineers to equipment, procedures and technology used in design, development, and research associated with industry accepted engineering practices.

In this relation, there is a need for these service-oriented laboratory facilities to continuously improve as well as sustain compliance to demonstrate the added value to the education institution's directives. Compliance management is the continual process of monitoring and assessing engineering laboratory facilities which critically involve conducting regular quality checks that signify priorities on regular maintenance and service on its teaching and research related asset (Deljo Pmc, and J&K 2022; Molinéro-Demilly et al. 2018).

Modern engineering laboratories contain many types of complex equipment that may pose electrical hazard if safety aspect is overlooked due to non-compliance. Typically, for service-focused engineering lab facilities rely on the people, process, and technology aspects. There is however a body of evidence (Wadhwa et al. 2012; Galli, Chiclana & Siew 2021; Feisel & Rosa 2005) that indicates that the root cause of non-compliance in engineering laboratories facilities can often being traced back to procedures not having been followed which are dominantly associated with human errors and work or process ignorance. In light of this, interest towards enhancing the management of compliance requirement on these service-oriented laboratory facilities has been a growing concern.

With regulatory and service level compliance requirements for these laboratory facilities becoming more challenging, time consuming and prone for human errors, existing management tools and manual processes may not scale to the task. Consequently, reliance on advancement in digital technology and Internet of Things, radio frequency identification (RFID) has gain increased attention in many industrial segments in terms of improved operational efficiency, efficient asset management as well as positively meeting compliance requirements of their business (Manghani 2011; Gasca 2012; Meyer 2012; Ninsiima Kasozi & Brandon III 2018).

This paper introduces a system for managing process compliance in engineering laboratories using RFID technology. Its main contributions are: (1) developing an automated compliance management system, (2) creating a graphical user interface to display compliance status, and (3) generating analytical reports using informatics to support tracking and record-keeping. RFID technology enables real-time data collection and analysis from lab equipment, allowing for timely alerts and follow-up reports on potential compliance issues. This approach helps identify and resolve problems early, meets stakeholder needs, and reduces risks and resource waste.

Thus, it is envisaged that effective management of compliance requirements driven by innovative digital technologies can provide the opportunity for strategic planning for improvements and contribute enormously to the success of meeting expectations of stakeholders and subsequently provide the opportunity for strategic planning for improvements.

COMPLIANCE PROCESSES FOR ENGINEERING LABORATORY

Engineering laboratory is as an integral part of academic resource in engineering education as it forms as the primary vehicle where basic experimental skills are learnt by systematically performing a set of prescribed and suitably designed experiments. In fact, the engineering laboratory is a distinctive feature in teaching and learning and forms one of the important concerns of engineering students in choosing their university to pursue their study.

Consequently, these facilities house a variety of tools, machines as well as test and measurement equipment in view of exposing student engineers to equipment, procedures and technology used in design, development, and research associated with industry accepted engineering practices, which forms as assets that absorbs a sizeable surge in investments annually.

The following is the list of laboratory facilities of the School of Engineering, UOW Malaysia Glenmarie Campus as shown in Figure 1.

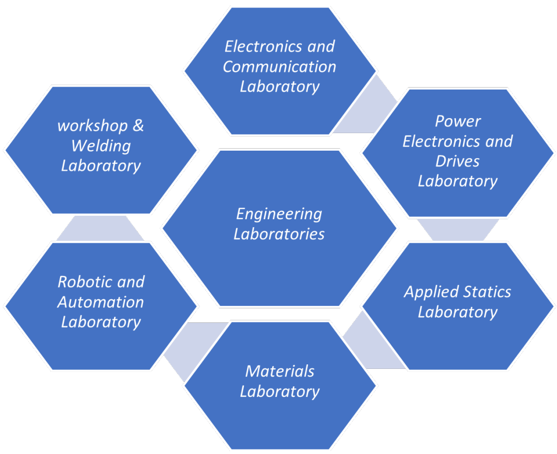


FIGURE 1. The Current Practice of Composition in Engineering Laboratories, UOW Malaysia

The engineering laboratory environment facilitates the conducting of practical activity that allows students to gain a first-hand experience with course concepts which has direct bearing towards enhancing cognitive abilities, developing good engineering attitudes as well as inquiry-based learning. Hence, the quality of teaching and learning experience depends on the extent of the adequacy and compliance of engineering laboratory facilities. Thus, critically entails monitoring and assessing teaching and research related assets of the service-focused engineering lab facilities to meet the requirements stipulated by standards, regulations, and service level.

Compliance assessments are very important for the care and management of engineering laboratory facilities.

This is to ensure the viability and long-term safety of the investment as well as meeting and maintaining quality, health and safety, and resource waste. According to work by (Khalidand & Kadni, 2000; Eyire, 2013; Mohamad, Yasin, & Rahman 2012) compliance management is an ongoing process and there are many arguments in favour of strong compliance management. The reason being it:

1. reduces organizational risk.
2. ensures employees adhere to business policies.
3. reduces the chance of negative publicity.

In this relation, the International Organization for Standardization (ISO) 9001 certification has gain wide popularity as it provides a process-oriented approach to documenting and reviewing the scope and procedures required to achieve effective quality management that meets customer and regulatory requirements and to demonstrate continuous improvement ("Laboratory Quality Management System Handbook Laboratory Quality Management System" 2011; "2016 Quality and Reliability Manual," 2016; Molinéro-Demilly et al. 2018).

Under this compliance certification, there are two types of non-compliance namely minor and major. The minor noncompliance is regarded as minor failures. Examples of a minor nonconformity for processes are unauthorized change in documentation, mis segregation of nonconforming products, and improper machine calibration and maintenance. On the other hand, major noncompliance reflects significant failure to meet quality requirements. Examples of major nonconformity are frequent unauthorized changes, failure of executing scheduled maintenance and services task of equipment as well as personnel who failed to take corrective action on a root cause of an issue (Zeba, Brod, & Strossmayer, 2018; Mustapha et al. 2020).

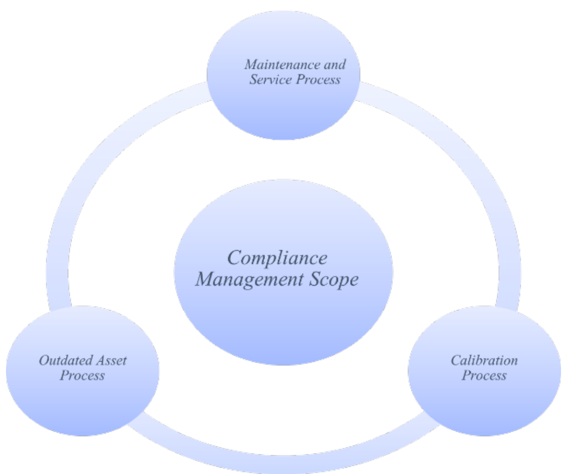


FIGURE 2. The Compliance Management Processes

As highlighted in Fig 2, typically, the management of compliance requirement involves processes as below:

MAINTENANCE AND SERVICES PROCESS

In this scope, test and measurement instruments have a high demand in laboratory testing. Maintenance and service of this equipment helps identify the defective or substandard equipment and machinery that undergo timely degradation. Thus, meeting compliance requirements under this scope helps monitor and increase the shelf life, performance, accuracy, and efficiency of these devices.

CALIBRATION PROCESS

Routine and timely calibration of equipment and machines is crucial to keep instruments in optimal condition and subsequently ensures that the data captured during experimental, or research activity are reliable. Thus, management of compliance requirement under this scope helps keep an automated schedule and subsequently instrument management more efficient and reduces the risk of possible errors.

OUTDATED ASSETS PROCESS

Engineering facilities handle a wide range of complex test and measurement instruments, making it important to track and manage these assets to maintain smooth operations. Compliance also requires monitoring outdated equipment to ensure only properly functioning instruments are used, which can affect budgeting for new investments. Failing to do so may lead to operational disruptions and increased costs.

Despite efforts to comply with regulations, many facilities fall short due to overlooked processes or inaccurate record-keeping. Non-compliance often means that required procedures are not being followed properly, which can be identified through audits, inspections, complaints, or testing. Addressing these issues requires corrective actions. In higher engineering education, maintaining quality compliance is essential, and using innovative technologies has become critical for effectively managing laboratory processes and achieving regulatory standards.

RFID AS ENABLER TECHNOLOGY FOR COMPLIANCE

Deployment of emerging technologies helps academia answer questions from regulators about credibility, measurement, continuous improvement, and accountability. On recognizing these expectations, academia that supports engineering laboratory facilities must be digitally transformed to move away from fallible manual systems where inconsistent practices were causing inefficiency and subsequently failing to meet compliance requirement.

In a bid to avoid such predicament, deployment of Radio Frequency Identification (RFID) based on the Internet of Thing (IoT) forms as innovative solution to manage compliance requirements. A technology that is dominantly used as automated monitoring system has gain wide popularity in many sectors ranging from smart agriculture, medical and healthcare, banking, retail and sales, smart manufacturing as well as logistics and warehouse inventory. RFID avoids the limitations of barcode scanning, which requires line-of-sight access to each barcode and can only be used to scan one item at a time. RFID tags can be read automatically, in groups and from a distance making it possible to connect devices to the internet and monitor them remotely. Thus, the main benefits of RFID are optimizing resources, quality customer service, improved accuracy, and efficient business and operational procedures (Ngozi & Halima 2015; Mr. 2020; Liu, Yang, & Lu 2015).

METHODOLOGY

This RFID driven systems as shown in Figure 3 comprise a RFID reader, RFID tags, and two antennas (Mi-UCP 400 – Frequency 902 to 928MHz from MDT Innovations Sdn Bhd) which is connected to a wireless router (Wavlink N300) to communicate with Graphical user interface application. The RFID tags (3M) are placed onto the identified test and measurement equipment which will be well covered and detected by two wall mounted robust antennas. The RFID reader (Impj Speedway Revolution R420) communicates using electromagnetic fields with the antenna to transmit vital information captured from the tag. This is done wirelessly by setting up a router to the reader.

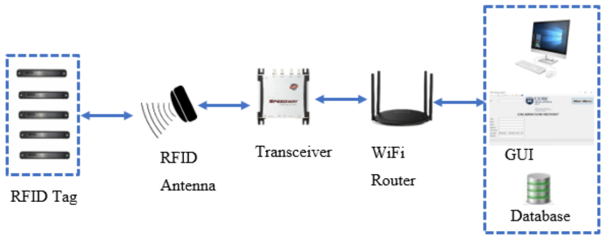


FIGURE 3. The RFID Functioning of The Database System

The data gathered will be processed by a GUI (designed by using Microsoft Visual Basic) which subsequently triggers a change of status with regards to that test and equipment. The entire revolves on tracking the process related to three compliance requirements namely calibration, maintenance, and service as well as outdated assets based on data captured on real-time basis. In fact, real-time data are collected for respective compliance processes. This entails investigation and monitoring a variety of different data about the instruments and equipment in the engineering laboratory facilities. Subsequently, the system can generate a predictive analysis output using informatics as a diagnostic component by checking critical information pertaining to required processes of various test and measurement equipment at a specific workstation.

The study and its associated experimental activities were carried out in the Electrical & Electronics Systems Laboratory which is located at the second floor of the University of Wollongong Malaysia (UOWM) at Glenmarie, Shah Alam campus. This electrical and electronic laboratory houses 36 different test and measurement equipment which are tagged with a unique identification. The layout of the floor plan for the deployment of this RFID based system is shown in Figure 4 below.

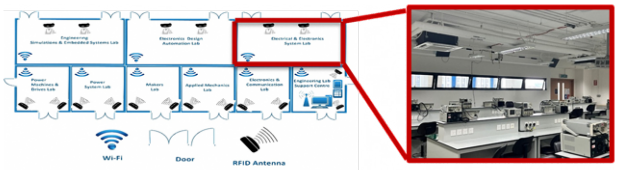


FIGURE 4. Deployment Of RFID Technology In Laboratory Facilities (Betharajoo, Paramasivam & Chua 2021)

FIGURE 5. Hardware Setup at Engineering Laboratory (Betharajoo, Paramasivam and Chua 2021)

Figure 5 indicates the hardware configuration which includes (a) RFID antenna, (b) Wi-Fi router, (c) RFID reader (d) RFID tag installed at the Electrical and Electronics System laboratory. This has been set up at the top back part of the laboratory such that it can capture the area of the laboratory.

The implementation involves the two antennas to be mounted beside the exits of the laboratory whereby a pair of brackets are used to hold the antenna at an angle of 45 degrees position to capture the best frequency range for the tags on the equipment as shown in Figure 6. The frequency range for this set up falls within 865 MHz to 867 MHz frequency. The distance between the two brackets is 2 meters range and the height is 2.5 meters. A single reader is used and operates on a wireless mode to capture the data from the RFID antenna. This is important to ensure the coverage is well covered to establish effective communication for process tracking (Betharajoo, Paramasivam, and Chua 2021). On the informatics section, visual basic is used to design and develop the GUI interface to relay vital information related to compliance status of the test and measurement equipment via network. Visual basic provides a convenient platform for users to easily modify code by simply dragging and dropping objects and defining their behaviour and appearance. The GUI interface designed for this lab management system to track compliance requirement consists of five processes namely calibration process, maintenance and service process, outdated assets process, inventory tracking, and laboratory monitoring.

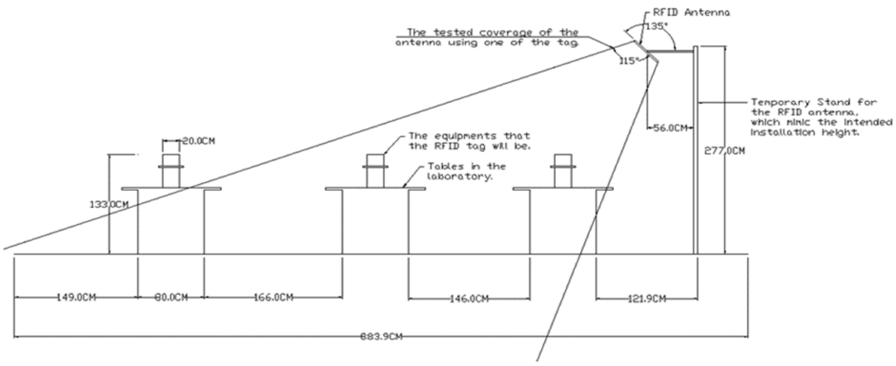


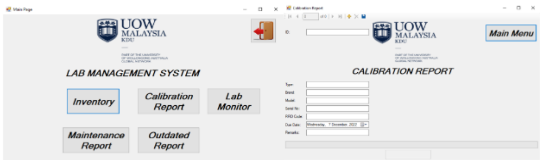
FIGURE 6. A Sketch of the Antenna (45°) and Its Beam Width (Side View)

FIGURE 7. Calibration Due Date Sticker

In the conventional process of calibration, a standard practice involves affixing a sticker onto the top of each test and measurement equipment. This sticker typically contains crucial information such as the certificate number, serial number, tag number (if applicable), calibration date, and calibration due date. The process of this is illustrated in Figure 7.

However, in scenarios where the number of test and measurement equipment units is substantial, keeping track of individual due dates can pose a significant challenge. This complexity arises due to the varying calibration schedules for each piece of equipment, leading to potential issues with past due dates.

The GUI provides a list of test and measurement equipment such as oscilloscope, power supply, function generator and spectrum analyser that needs tracking of compliance in terms of functionality, life span as well calibration. The system is coded to uniquely toggle on each process in a non-concurrent mode. The GUI allows selection of test and measurement items and its related such as serial number, model number and brand. The overall details and particular of various test and measurement equipment will be housed in an external database. The designed and developed GUI of this compliance requirement for laboratory management system is shown in Figure 8 (a) and 8 (b) below.



(a) (b)

FIGURE 8. Design and Develop GUI Of Compliance Requirement

The compliance process tracking of the system is illustrated using a flow chart as shown below in Figure 8. In this system, the due date is selected from a drop-down calendar to initiate and monitor the next cause of action to be taken by the support team. This tone, compliance status will appear automatically to signify meet compliance, minor and major forms a critical input to the system to ensure no break-down in the work cycle. The system is coded to perform a comparison between due date and current date and subsequently, trigger alerts through colour tones. The system is designed to reflect three colour tones which are green, yellow and red. In reference to the colour. The system is created to provide visual notification as a timely reminder to the support team to take the next relevant action to fulfil the compliance requirement. The system adopts SMTP protocol to generate email notification at various intervals to reinforce compliance to near non-compliance situation as well as non-compliance status.

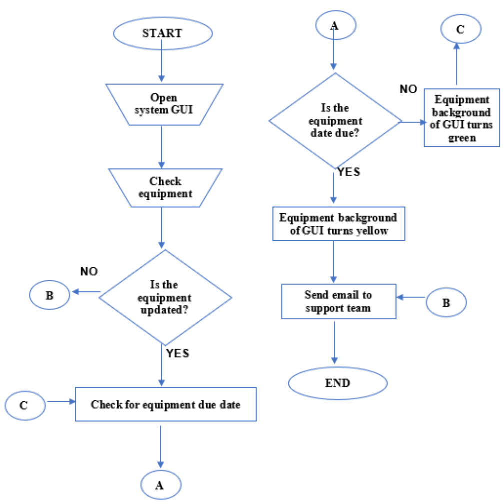


FIGURE 9. Flow Chart of the Compliance Management Process

The systematic tracking of compliance processes within the implemented system is well depicted through a meticulously designed flow chart, as elucidated in Figure 9. Within this innovative system, a pivotal component involves the selection of a due date from a user-friendly drop-down calendar. This due date acts as a key trigger, initiating and monitoring the subsequent course of action to be undertaken by the support team. This interactive input proves critical to the system, ensuring a seamless and uninterrupted workflow without any breakdowns in the compliance management cycle.

To enhance the operational efficiency and awareness of the compliance status, the system is intelligently coded to perform a real-time comparison between the selected due date and the current date. Subsequently, the system triggers alerts through distinct colour tones, introducing a visual element that simplifies the interpretation of compliance status.

RESULTS AND DISCUSSION

As mentioned previously, the GUI provides a list of test and measurement equipment such as oscilloscope, power supply, function generator and spectrum analyzer that needs tracking of compliance in terms of functionality, life span as well calibration.

The coded sequence would perform a comparison between the real time and date against the due date of the test and equipment and the check is carried out on a cycle routine manner. On the other hand, if it strays away from the required service period, the system will change into another colour tone.

Subsequently, a mathematical computation will be performed to determine the compliance status. In the initial stage, the process tracks a 100% with an indication of green colour bar and compliance status "COMPLY" generated. Thus, provides a visual type of notification in terms of colour tone. In this case, continuous monitoring and tracking is performed daily to determine the validity of compliance requirement of test and measurement equipment. The coded sequence operates the system based on equation as below:

$$B_d = \frac{D_t - D_c}{D_t} X\ 100 \qquad (1)$$

B_d = Balance days in percentage, D_t = Total days, D_c = Current days

For example, the calibration process for an oscilloscope which has a due date of 31st December 2023, will indicate the progress bar to be at 100% as the balance days is at 365 days and the total days also at 365 days. The system will continuously track the process and highlight 'COMPLY" status until 75% when it has balance days of approximately 275 days over the total days.

$$B_d = \frac{365 - 220}{365} X\ 100 \qquad (2)$$

$$B_d = \frac{365 - 127}{365} X\ 100 \qquad (3)$$

The mechanism goes on tracking and eventually when there is a balance of approximately 180 days, the progress will be at 50%. At this stage, the status indicator will be changed from green to yellow stating as "MINOR". This forms as an early alert to the support team to take prompt action for the item.

In this case, the early alerting allows the support team to proceed into sourcing and negotiating with suitable vendors and service suppliers to solve the calibration requirement in a timely manner. In reinforcing the criticality of the situation, an email notification would be generated to the support team as well as the head of department as a record for further action.

When it reaches approximately 90 days, this will indicate the progress bar to be at 25% and when is at 0 days, will be at 0%. In these stages of 25% and 0%, the status indicator will change from yellow to red and will be stating it as "MAJOR". Thus, signify a breakdown in the compliance requirement for the said process. Again, an email will be generated and sent out to the support team and the department head on of the given situation.

(a) (b) (c)

FIGURE 10. The compliance process progress over the time, (a) 100% (b) 50% (c) 25%

In reference to outdated test and measurement equipment, there is a lifespan for each equipment in terms of functionality and useability due to wear and tear effect. In this case, this will be described as outdated equipment. This outcome assists the support team to perform preventive action on potential safety risk by highlighting to the management on budget matter for future purchase.

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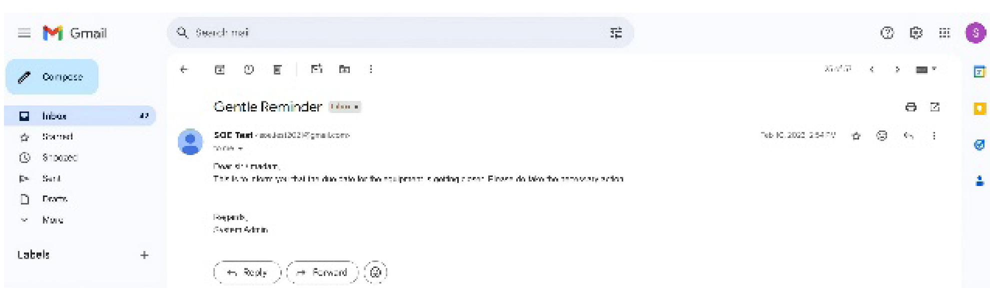

FIGURE 11. Email Message

The system is developed to initiate transmission of electronic mail notification to remind the support team on compliance issue as an early warning preventive action. This notification strengthens the compliance requirements in order not to further delay the specific task and if this delay persists, a second electronic mail will be sent to the Quality Auditor of the institution.

FIGURE 12. Calibration Compliance Statistics Data

The calibration compliance system utilizes statistical data and graphical representations to provide real-time alerts and prompts. By setting a clear threshold of 182 days and employing color-coded indicators, the system ensures that the support team is well-informed and can take prompt action before equipment falls into non-compliance:

1. *Green (182 to 365 Days):* This stage indicates that the calibration is within the acceptable timeframe. Equipment calibrated within this period is considered compliant, and no immediate action is required. The green zone reflects optimal compliance, ensuring that equipment performance remains reliable and accurate. The intention is to avoid the calibration compliance work order to progress beyond 182 days which falls under a minor compliance stage (within 183 to 208 days).
2. *Yellow (92 to 182 Days):* The yellow color code serves as a warning that the calibration is approaching or has exceeded the optimal interval. A yellow dotted line represents the threshold of 182 days. Once equipment approaches this line, the support team interprets that calibration needs to be addressed to prevent falling into non-compliance.
3. *Red (0 to 92 Days):* If calibration exceeds 273 days, it falls into the red zone, indicating a major compliance issue. This stage highlights a significant lapse in the calibration schedule, which could compromise equipment accuracy and overall lab performance.

In a laboratory setting, tools are categorized as faulty or non-functional based on specific conditions:

1. Test Pens: Considered faulty if they fail to produce a clear indication of electrical presence or exhibit inconsistent readings.
2. Soldering Irons: Deemed non-functional if they do not reach the required temperature for effective soldering, have broken or frayed cords, or inconsistent heat distribution.
3. AC Adapters: Faulty if they do not supply stable voltage, cause intermittent power issues, or show physical damage like frayed cables or burnt connectors.
4. Digital Multi-Meters: Non-functional if they display erratic readings, fail to measure correctly across various modes (voltage, current, resistance), or have a damaged display.

5. Mini Hand Drills: Categorized as faulty if they exhibit inconsistent rotation, fail to start, or have damaged components affecting their drilling performance.

CONCLUSION

Engineering laboratory facilities in academia are always viewed as service-oriented entities that are expected to continuously improve to sustain compliance to demonstrate the added value to the education institution's directives. As processes are required to be tracked and monitored to avoid noncompliance, deployment of innovative and emerging technology of IOT enabled RFID system are much needed in this context as well as to streamline the inevitable audit process. Reliance on technology with notification alerts integrated with data analytics capabilities helps the laboratory facilities to efficiently manage and respond to these data to better comply with rule and regulation to ensure that test and measurement equipment and related machine are safe and in working order.

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DECLARATION OF COMPETING INTEREST

None.

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