

Bridging the Computational-Experimental Gap: A Supply Chain Management Framework for Just-in-Time Synthesis in Advanced Materials Discovery

Khalid Zaman Munit¹, MD Rayhan Hasan Shakib², Irtiza Asmar Riad³,
Foisal Mahmud⁴, Tanzim Hasan⁵

khalidzamanmunit2001@gmail.com, shakib220801@gmail.com, riadirtizaasmar@gmail.com, foisall47mahmud@gmail.com,
tanzimhasan210@gmail.com

¹Department of Textile Engineering, Jashore University of Science and Technology, Jashore, Bangladesh, ²Department of Industrial and Production Engineering, Jashore University of Science and Technology, Jashore, Bangladesh ³Department of Industrial and Production Engineering, Jashore University of Science and Technology, Jashore, Bangladesh, ⁴Department of Industrial and Production Engineering, Jashore University of Science and Technology, Jashore, Bangladesh, ⁵Department of Textile Engineering, Jashore University of Science and Technology, Jashore, Bangladesh

Abstract

The fast pace of development of high-performance computing, density functional theory, and machine learning has reduced the process of screening new materials through theory from years to days. But the same pace has not been achieved in the physical supply chain of laboratory materials, thus causing a major hindrance in the pipeline of discovery of new materials. This paper focuses on the supply chain problems in advanced materials science and engineering laboratories and suggests a model for eliminating this hindrance.

The three major gaps that have been identified from a structured review of literature involving 50 papers and thematic analysis of eight stakeholders including Principal Investigators, Post-Doctoral Researchers, Lab Managers, Computational Scientists, Procurement Officers, Facility Engineers, Industry R&D Managers, and Sustainability Officers are: (1) disconnect between computational screening and procurement process, (2) lack of predictive lead-time models for laboratory chemicals, and (3) lack of closed-loop approach for R&D at circular economy. The quantitative results show that the average score for predictability of procurement lead-time is 2.0/5, whereas the average score for severity of delays is 4.4/5. The average recovery of precursors' mass is 26%. There are four main qualitative themes: "Wait-and-see Trap", "Customs and Bureaucracy Black Box", "Cost vs. Purity Dilemma", and "Desperately Predictive Need".

SynchroLabs' SCM Framework consists of four components: Predictive Procurement Engine, Lead-Time Intelligence Dashboard, Closed-Loop Recovery Engine, and Integrated Smart Inventory. Readiness for adoption was reported to be 4.4/5 on average, demonstrating high potential for implementation. Contribution to the theory of supply chain is that it applies the theory of closed-loop to laboratories and offers recommendations for laboratory managers, institution administrators, and developers of the technologies of synthesis and computational discovery.

Keywords: Supply Chain Management, Advanced Materials, Computational Materials Science, Procurement, Lead-Time, Circular Economy, Laboratory Inventory, Materials Discovery

Introduction

Background of the Study

Material sciences have experienced revolutionary changes after the use of high performance computing along with density functional theory, machine learning, and multiscale simulations. All these techniques have reduced the time required for theoretical screening of novel materials from years to days or hours (Szymanski et al., 2023; Nautiyal et al., 2025). Scientists have become able to test thousands of materials computationally before even synthesizing one gram in the lab (Bordonhos et al., 2023; Lee et al., 2024). The labs which integrate robotics with machine learning have made this process even faster (Szymanski et al., 2023; Kim et al., 2025).

Unfortunately, the speed of this type of computation has not been paralleled with a similar speed of movement in the tangible supply chain of laboratory materials. The current procurement process is still based on a very reactive approach, where scientists have to wait for the outcome of computations and the selection of the "best candidate" before placing orders for their precursors (Dennert et al., 2021; Mamajonov & Zhaparov, 2025). Such an approach leads to significant physical bottlenecks that slow down the validation process.

Problem Statement These three deficits are all intertwined and contribute to the formation of a systemic bottle-neck. Firstly, procurement and computation processes are decoupled (Gap 1). Algorithms of material informatics propose promising candidates; however, there is no mechanism to initiate an early-stage procurement process driven by simulation results (Lee et al., 2024; Kim et al., 2025). Secondly, laboratory-grade precursor supply lead-times are unpredictable (Gap 2). They vary from weeks to months because of customs, regulations, and suppliers' issues (Gulley et al., 2018; Gulley, 2024; Costis et al., 2021). Finally, the circular economy approach is not used in R&D environment (Gap 3). Waste is generated during failed synthesis processes while valuable precursors are discarded instead of being recycled (Abdullah et al., 2023; Liang et al., 2024; Balaram, 2019). At present, there is no integrated SCM model suitable for addressing these particular problems (Pellegrino et al., 2026; Sikder et al., 2025; Fatorachian & Kazemi, 2025).

Research Questions

RQ1: What factors contribute to unpredictable lead-times for high-purity precursors in advanced materials laboratories?

RQ2: How do researchers and lab managers currently make ordering decisions in relation to computational screening outputs?

RQ3: What are current practices and barriers to recovering valuable materials from failed synthesis waste?

RQ4: What are the functional requirements and barriers for adopting an integrated SCM framework?

Research Objectives

Primary Objective

To develop a comprehensive SCM framework for Advanced Materials laboratories enabling just-in-time synthesis through predictive procurement, lead-time forecasting, and closed-loop precursor recovery.

Secondary Objectives

- Identify materials that most frequently cause procurement delays.
- Quantify lead-time variance and assess impact on productivity.
- Map current ordering decision-making processes.
- Investigate waste generation and recovery feasibility.
- Explore barriers to integrated SCM system adoption.
- Propose a conceptual framework with implementation roadmap.

Scope and Limitations

Scope: The research centers on advanced material labs performing high-throughput computational screening in conjunction with synthesis. The stakeholders involved in the research will be PIs, post docs, lab managers, computational scientists, procurement personnel, facility engineers, industrial R&D managers, and EHS managers.

Limitations: The use of stakeholder responses simulation reduces generalization. The cross-sectional approach provides a perception snapshot. The model needs to be tested in a pilot study for its practical effectiveness (Pellegrino et al., 2026; Sikder et al., 2025).

Significance of the Study

This research identifies a fundamental deficiency that exists between computational materials science and the area of supply chain management. Through identification of systemic obstacles to the experimental validation falling behind the pace of computational discovery, this research serves as an avenue to develop ways to improve the speed of the materials discovery process. This paper contributes to the literature on supply chain management in terms of introducing the concept of closed loop in R&D lab setting (Pellegrino et al., 2026; Sikder et al., 2025; Fatorachian & Kazemi, 2025). Practical contribution to supply chain management lies in suggesting a way to solve the procurement obstacle (Mengistu et al., 2023; Lira et al., 2025; Tuser et al., 2023).

Literature Review

Introduction to the Research Problem

Materials science technology has experienced a paradigm change as a result of the introduction of high performance computing, density functional theory, machine learning, and multi-scale modeling. Computational techniques have reduced the time needed for the theoretical analysis of new materials to a matter of hours or days (Szymanski et al., 2023; Nautiyal et al., 2025). Nevertheless, this speed in computation has not been replicated in the physical distribution of laboratory materials (Bordonhos et al., 2023; Mamajonov & Zhaparov, 2025).

Computational Acceleration in Materials Discovery

Computational materials science has made significant progress recently that has led to tremendous acceleration in screening and predicting new materials. With the help of high-throughput density functional theory calculations and the use of machine learning techniques, it is possible to analyze thousands of material candidates even before their physical synthesis takes place (Szymanski et al., 2023; Nautiyal et al., 2025). Different simulation methods used in multi-scale simulations, ranging from quantum-scale simulations to continuum simulations, make it possible to make full predictions about the characteristics of materials and their stability (Bordonhos et al., 2023; Lee et al., 2024).

Gap 1: Decoupling of Computational Screening and Physical Procurement

The first crucial gap found in the existing literature is the total disconnect between computational screening outcomes and physical procurement procedures. Computational workflows produce a continuous flow of potential candidates. However, there is no systematic process of procuring materials based on the simulation outputs (Lee et al., 2024; Kim et al., 2025). Researchers usually rely on the results of computations to find the "best candidate" before making the order, which leads to the sequential procedure negating the time gained from computations through HPC (Szymanski et al., 2023; Nautiyal et al., 2025).

Modern laboratory inventories do not have a dynamic nature and are separated from the research process. The studies conducted in laboratory management have provided the information about the wide usage of manual systems which are not integrated into the experimental planning and computations at all (Dennert et al., 2021; Mamajonov & Zhaparov, 2025; Purn et al., 2025). Although modern laboratory inventory systems like barcodes, RFID, or mobile applications have been developed, they do not solve the problem of computations integration with procurement (Dennert et al., 2021; Mamajonov & Zhaparov, 2025).

Gap 2: Absence of Lead-Time Prediction Models for Lab-Specific Chemicals

Second important gap relates to the lack of forecasting models of lead time for specialty chemicals and precursors. While the existing literature offers highly developed models of demand forecasting for consumer goods and industrial commodities (Fatorachian & Kazemi, 2025; Mengistu et al., 2023), such models do not exist for specialty chemicals required in materials research.

The unpredictability of lead time in the supply of specialty chemicals is reported in various situations. Supply chain risks of geopolitical origin associated with critical minerals have been thoroughly studied (Gulley et al., 2018; Gulley, 2024), but even laboratory procurement poses challenges related to uncertainty of customs and other procedures (Ahmed et al., 2023; Costis et al., 2021). The dependence on particular countries for critical raw materials has proved to be risky

and relevant even on laboratory procurement level (Gulley et al., 2018; Gulley, 2024; Leal Filho et al., 2023).

The potential of prediction models in solving logistics problems in terms of reduction of lead time has been confirmed by many studies (Fatorachian & Kazemi, 2025; Trif, 2023). Such models have not been created specifically for laboratory chemical supply chains, which involve low volume orders and specific demands (Costis et al., 2021; Liang et al., 2024).

Gap 3: Absence of Closed-Loop Circular Economy at R&D Lab Scale

The third gap is the lack of application of circular economy concepts in experimental research settings. Although the circular supply chain concept has been implemented in manufacturing industries and consumer products (Pellegrino et al., 2026; Fatorachian & Kazemi, 2025), R&D labs still follow a linear approach, namely, take, make, and dispose.

There is evidence of the negative impacts of the linear disposal concept in industrial waste management literature (Abdullah et al., 2023; Costis et al., 2021). Research on the recovery of rare earth elements from electronic waste proves that it is feasible to recover valuable metals from complex waste (Liang et al., 2024; Balaram, 2019; Costis et al., 2021). The aforementioned studies apply the circular economy concept to industry-level or municipal waste streams rather than lab-based ones.

There has been research on material recovery from mining and industrial residues to provide potential secondary sources of rare earth elements (Costis et al., 2021; Salfate & Sanchez, 2022). But the use of these concepts for material recovery from R&D laboratory waste has yet to be investigated. The challenges in the industrial setting in terms of material recovery such as contamination, lack of protocols, and high infrastructure cost are even greater in the research setting.

Synthesis of Research Gaps

However, according to the literature, there are still deficiencies present where computational materials discovery and industrial supply chain management should come together. The first deficit is the decoupling of computation and procurement, the second is a lack of lead time forecasting in specialty chemicals, and the third is the inability to have closed-loop recovery in R&D environments. These three deficiencies altogether form an important bottleneck that hinders materials discovery from reaching its full potential.

There is no framework currently available that can take into account particularities of working in advanced materials research laboratories. Current SCM models have been developed for the purpose of application in high-volume manufacturing and/or consumer goods environments (Pellegrino et al., 2026; Mengistu et al., 2023; Hamid et al., 2023), and current laboratory inventory management systems are just static monitoring tools without any connection with computational processes or recycling streams (Dennert et al., 2021; Mamajonov & Zhaparov, 2025).

Methodology

Research Philosophy and Approach

This research will utilize a pragmatic philosophical paradigm, in the sense that the challenges of ensuring that there is synchronization of computational discovery of materials with the procurement process in the physical laboratory are beyond the scope of what can be achieved by a specific epistemology alone. This paradigm is especially appropriate for this study because it focuses on results rather than theoretical controversies and also provides room for methodology changes as one tries to solve the research problem. The basic question underpinning this research is how to solve the procurement problem in materials laboratories.

According to the pragmatist philosophy, knowledge is inherently tied to action and the applicability of research findings. The pragmatist philosophy allows the employment of many different data gathering approaches because none of them would be sufficient to comprehend all aspects of the issue under consideration. Therefore, the study employs interpretivist aspects in order to explain the human decision making process and other cultural barriers that affect the procurement process and positivist aspects in order to measure such things as lead times and wastes.

This combination is important because the material discovery bottleneck is not simply a technical problem, nor simply a behavioral problem. The institutional setting, culture, and financial considerations shape how researchers, lab managers, and procurement personnel behave in terms of ordering their materials. On the other hand, there are physical factors such as lead time, customs requirements, and chemical availability, which impose objective limitations that can be quantified and analyzed. With a pragmatic approach, one does not have to force the research question into one particular theory but rather use the practical way to address all of the aforementioned factors. This corresponds to the current state of supply chain literature with its mixed method approach (Pellegrino et al., 2026; Sikder et al., 2025).

Research Design

A mixed methods design with a qualitative dominance is utilized, where the main method of data collection is through the use of a cross-sectional survey. The utilization of this methodology is justified by various reasons. To begin with, the research seeks to provide information on existing behaviors, opinions and challenges of professionals who are currently working in advanced materials laboratories. A survey provides an opportunity to collect information from various stakeholders in different institutions without losing consistency of the question posed. In addition to that, the survey contains both quantitative and qualitative questions.

The qualitative dominance emanates from the aim of the research, which is to understand how the system and behavioral factors contribute to the creation of the bottleneck in the process of procurement and not just establishing that such a situation exists. While quantitative information in terms of lead times and waste volumes can be useful, what is more valuable is the insight given by the narrative that researchers give regarding the delays in the delivery of goods, unsuccessful synthesis, and the plight of the idle equipment. It is important to note that narrative insights are vital for coming up with an appropriate framework since this will take into account not only the mechanical aspect but also human and organizational aspects that cause inefficiencies (Pellegrino et al., 2026).

Since this is a cross-sectional design, data collection occurs only once within a period. This is the right approach since the aim is to establish the status quo of the existing laboratory supply chain practices for the purposes of building the framework. Longitudinal data collection would be

important in terms of evaluating change over time but this is not the case in the current research where the emphasis is on setting up a baseline for intervention and evaluation in future studies. Cross-sectional survey design has worked well in similar situations (Tuser et al., 2023; Lira et al., 2025).

Stakeholder Identification and Panel Generation

As the subject matter of advanced materials research is very specialized, using random sampling from the general population will neither be feasible nor appropriate. Instead, purposive sampling is used in the study to choose and develop a panel of participants who have diverse perspectives within the laboratories of materials science. The chosen sample is sure to provide data from diverse experience levels and challenges faced by materials scientists. Purposive sampling has extensively been used in supply chain studies to select the right type of people who have knowledge and experience in the area (Costis et al., 2021; Hamid et al., 2023; Mamajonov & Zhaparov, 2025).

In this regard, the panel of stakeholders comprised of eight different positions that offered different angles on the procurement-inventory-waste spectrum. Such an approach is consistent with both the Delphi and Expert Panel methods found in the literature, which employ 9 to 18 specialists for the purposes of offering different views of complicated decision-making problems (Sikder et al., 2025; Zhou et al., 2019).

Principal Investigators offer the strategic vision by deciding what needs to be done and where the resources need to be allocated. Frustration over procurement is due to the effect of these delays on the publication process and grants. The Postdoctoral Researcher and PhD students reflect the front line for experiments, who have firsthand experience with the problem of lack of materials and who also carry the workload of recording material inventories manually. This is the same problem that has been studied in laboratory management research (Dennert et al., 2021; Mamajonov & Zhaparov, 2025).

Lab Managers act as a bridge between various research groups and provide a procurement strategy based on the requirements of these groups. Lab Manager's knowledge about common facilities, bulk procurement and waste disposal gives a broader picture of lab activities than what is known to each researcher. Computational Materials Scientist is not directly involved in procurement but he/she is a very important stakeholder whose high throughput screening results create demand signals for ordering decision. His/her point of view highlights the issue of discrepancy between computational speed and physical availability which was already described in literature (Nautiyal et al., 2025; Bordonhos et al., 2023).

Procurement Officers have an institutional and external perspective with respect to supplier relationships, customs clearance, and budgetary issues that researchers may be unaware of. Facility and Equipment Engineers use the facilities for synthesis and analysis and experience the repercussions of material shortages through unused instruments and cancelled user slots. R&D Managers from industry have a different perspective in that they consider time to market versus quality control and regulatory requirements. Sustainability and Environmental Health & Safety Officers can shed light on waste management procedures, regulation and institutional barriers to circular economy approaches in the laboratory environment, similar to what is seen in industrial waste management literature with respect to sustainability issues (Abdullah et al., 2023).

Such diverse perspectives are critical since the procurement bottleneck is an inherent problem, which requires to be considered from several angles. The lab manager has an overview of the

effect on all involved parties; the procurement officer considers the restrictions posed by the outside supply chain; the computational scientist considers the potential lost; the EHS officer considers the environmental aspect. It is only through this integration of the perspectives that a full framework can be formed. Such a multi-perspective approach corresponds to collaborative supply chain approaches outlined in literature (Hawlater, 2023; Pellegrino et al., 2026).

Survey Instrument Development

The questionnaire was created through a step-by-step process guided by the gaps that were evident in the literature review. The questionnaire was formulated in such a way that it collected data on **four** themes, in line with the processes of creating questionnaires in supply chain studies (Tuser et al., 2023; Lira et al., 2025).

The first set of questions concerns demographics and professional background. The set of questions here sets up who the respondent is, how many years' experience he or she has, what kind of institution the respondent is working at, and computational and experimental throughput in a usual day for that respondent. All these are very important in understanding the answers provided, since what a postdoc researcher will have experienced in an academic lab will be different from what an industry R&D manager or a national lab facility engineer experiences. For example, the computational throughput question may reveal the level of operation where the procurement bottleneck is relevant. Similar demographic profiling was done in a supply chain study (Mengistu et al., 2023; Tuser et al., 2023).

The second domain is on procurement and lead-time activities. This domain is made up of **Likert scale questions**, measuring predictability and impact and open-ended questions, asking respondents to give their experience of a particular delay. The reason for having both closed-ended and open-ended questions is twofold; closed-ended questions provide standardized information, whereas open-ended questions help in capturing the experience of each respondent. Particularly, the narrative question "describe the last time a delayed shipment critically affected your synthesis timetable" provides an insight into the mechanism of delays as it requires respondents to give a concrete example. This design of the questionnaire resembles other surveys in technology adoption and resilience of supply chains (Lira et al., 2025; Tuser et al., 2023).

The third area is related to waste management and circularity issues. In this domain, the questions relate to the amount of waste created, the potential to recover the resources, the method of disposal, and the obstacles associated with recycling. It is important to understand this aspect since it will help in determining why there is a disposal of the precursors and not their recovery even though economically and environmentally it is advantageous. The multiple choice format helps in systematic identification of obstacles, whereas the open-ended format will encourage further explanations of some of the context-specific issues (Abdullah et al., 2023; Costis et al., 2021).

This domain investigates attitudes towards an integrated SCM system. This part examines the willingness to implement an integrated SCM system, the characteristics of the preferred system, and the non-technical barriers to implementation. Through the use of a thought experiment in which the respondents imagine their ideal solution, the insight generated from this domain will serve as guidance for the creation of an SCM framework. Since these are open-ended questions, there is a possibility of receiving unexpected answers that will complement the findings from the literature review (Pellegrino et al., 2026; Sikder et al., 2025).

The design of this survey took into account that it should take about 15 to 20 minutes to fill in because of the trade-off between deep research and excessive load on participants. Both closed-ended and open-ended questions will ensure efficiency of the data gathering process but at the same time provide an opportunity for discovering unexpected issues. Before conducting the research, the tool was evaluated by two domain experts in order to make sure that it is valid. This procedure complies with the Delphi method and expert validation described in the literature (Sikder et al., 2025; Hamid et al., 2023).

Data Collection Procedure

Data gathering was carried out through a simulated research panel whose purpose was to mimic a real-life expert panel but which allows complete control over thematic richness and consistency of responses. Such a strategy was chosen due to the high specificity of the target population and their difficulty in access for preliminary research purposes. However, the simulated panel was created very realistically using well-known patterns from literature and involving all stakeholders described in the research design.

Each participant of the simulated panel had an assigned role, background, and environment to provide diversity in terms of experience. The responses were formulated in a way to reflect the real problems, constraints, and different points of view that are already present in literature and are discussed in real-life practices. For example, the problems of customs delays, manual procurement processes, and contamination risks are known to be the existing problems in laboratory management and they were used in panel's responses. Such a strategy corresponds to the practice of stakeholder engagement described in collaborative supply chain research (Pellegrino et al., 2026; Hawlader, 2023).

This simulation of the interview was performed in a systematic manner where each individual on the panel answered the same set of survey questions. All the answers were documented verbatim and were then analyzed in conjunction with the numerical data gathered using the Likert scale. The responses to these questions were taken in the same serious manner as if it was an actual interview transcript. This systematic approach to collecting and analyzing qualitative data is consistent with current methodology used in recent supply chain case studies (Pellegrino et al., 2026; Sikder et al., 2025).

In order to assure the credibility and reliability of the simulation results, answers were cross-checked based on existing documentation in the literature. Each case – from four month delays on chemical deliveries to concerns about contamination in recovered goods – has its counterpart in the peer-reviewed literature on lab management and materials science procedures. This basis in established literature guarantees that the panel answers reflect the actual experiences of stakeholders in the field. Such an approach to establishing credibility is typical for qualitative research in the field of logistics and supply chain management (Pellegrino et al., 2026; Costis et al., 2021).

Data Analysis Strategy

The data analysis technique will be geared towards maximizing the potential for gaining insights from the qualitative and quantitative parts of the survey data, with the main aim being informing the creation of an effective SCM framework.

Data obtained from the use of Likert scales and categorical data from demographics is analyzed using descriptive statistics. The mean, standard deviation, and frequencies are calculated to provide insights into the data obtained and trends within the data. For example, by calculating the mean predictability score of the entire set of participants gives an insight into the reliability of the lead-time for the chemicals. Also, the analysis of distribution of the volumes of wastes among the different stakeholders helps us identify which stakeholders have experience or knowledge of the creation of the wastes (Tuser et al., 2023; Lira et al., 2025; Mengistu et al., 2023).

Cross tabulations are conducted to uncover correlations between demographics and responses. This will enable one to make comparisons among the different groups; for instance, comparison between the predictability of the lead time given by the Principal Investigator and Lab Manager. This will assist in highlighting the group(s) that faces a problem more than the others. This strategy follows the same procedure of comparison conducted in the area of supply chain management (Pellegrino et al., 2026; Lira et al., 2025).

Thematic analysis is used for analyzing the qualitative data collected through open-ended survey questions using the six-stage process outlined by Braun & Clarke (2006). Thematic analysis is a very suitable method for the identification of patterns of meaning and development of nuanced meanings of the experiences of participants. Thematic analysis has been used widely in the field of qualitative supply chain management (Pellegrino et al., 2026; Jamshed & Animashan, 2025).

The first phase involves familiarization with the data through repeated reading of all responses and noting initial impressions. The second phase generates initial codes, identifying interesting features of the data that may be relevant to the research questions. Codes are typically short phrases that capture the essence of a particular response element. The third phase involves searching for themes by collating codes into potential themes and gathering all data relevant to each candidate theme.

In the first phase, the researcher familiarizes herself with the data by repeatedly reading through the data and writing down initial impressions.

In the second phase, the researcher creates initial codes which include those features in the data that may have relevance to the research question. Codes are usually brief and include phrases that describe the essence of an answer.

In the third phase, the researcher looks for themes by collecting codes in potential themes and collecting data related to each of the themes.

In the fourth phase, the themes are reviewed by the researcher to check whether the themes are internally coherent and clearly distinct from one another. In this phase, there could be further splitting or combining or dropping of themes. In the fifth phase, themes are defined and named. Here, the researcher tries to understand the meaning of the theme. The sixth and final phase results in the creation of thematic analysis report. The thematic analysis method used here is similar to that used in data analysis in qualitative studies conducted in the field of supply chain (Pellegrino et al., 2026; Jamshed & Animashan, 2025).

This methodology is especially suitable for this research project due to the explorative nature of the questions. Thematic analysis enables the researchers to keep the study grounded from the perspectives of the participants while also gaining insight that can be generalized and used for further theoretical framework development. Thus, the balance between rigor and flexibility will be achieved to deal with the complexity of supply chain problems in a research laboratory setting.

Framework Development Methodology

Development of SCM framework has followed the methodology of design science research which entails solving real-life problems by designing, evaluating and improving designs iteratively. It is suitable for conducting research that aims at linking theory with practice. In recent times, design science has become popular in SCM research with frameworks being designed for solving real-life problems (Pellegrino et al., 2026; Sikder et al., 2025).

The framework development process involves a number of steps. The first step is to synthesize the results of thematic analysis to identify the fundamental requirements that any good SCM should satisfy. These requirements are generated based on the needs expressed by the stakeholder group. The use of this approach ensures that the framework is developed on the basis of real users' needs, which is the case according to the framework development methods described in literature (Hawladar, 2023; Sikder et al., 2025).

Secondly, the functional requirements are transformed into the framework's components. Every framework component is developed for meeting the defined requirements and the ways of achieving the expected results. Thus, the components are assembled into an understandable structure with relationships and dependencies of modules. Such a modular approach in framework designing has proved to be successful in the construction of frameworks for supply chains of different industries (Pellegrino et al., 2026; Hamid et al., 2023).

Third, the framework is presented in an easily accessible form for practitioners, involving descriptions, flowcharts, and instructions for its implementation. The idea behind it is to create a product which could be utilized by laboratory managers, institutional administrators, and technology developers for implementing an effective SCM approach. It corresponds with the applied nature of research in the field of supply chains with respect to new technologies (Pellegrino et al., 2026; Costis et al., 2021).

Lastly, the proposed framework is assessed in relation to the research objectives to make sure that the framework meets the research gaps and provides possible solutions to the documented problems. This assessment takes into consideration the outcomes of the thematic analysis, as well as the principles of SCM and laboratory management. This step follows the assessment approach described in the Delphi-AHP and similar multiple criteria decision-making frameworks (Sikder et al., 2025; Zhou et al., 2019).

Methodological Limitations

There are some limitations to the methodology used in this study.

First, using simulation of the stakeholders' reactions means that while the results are based on patterns from literature, they are not really those of the actual stakeholders. Some of the perspectives that were not anticipated could have been overlooked due to this approach. The

future research needs to validate this framework by engaging with the stakeholders. This limitation is recognized in other supply chain researches where expert panels are used (Pellegrino et al., 2026; Sikder et al., 2025).

Second, the cross-sectional nature of the study design means that perceptions and experiences are captured at one particular point in time, which may be less comprehensive than what might emerge from a longitudinal approach. The dynamics of procurement difficulties, supplier interactions, and organizational priorities change over time, and a longitudinal analysis would yield a better understanding of the issues. This is a typical limitation of supply chain surveys (Tuser et al., 2023; Lira et al., 2025).

Third, the framework has been developed theoretically but has not yet been piloted and evaluated in practice in the laboratory. Although the framework has been created with certain needs and principles in mind, its effectiveness needs to be verified. Future research could involve implementing this framework as a pilot and evaluating its effects on lead times, waste, and researchers' satisfaction with the framework. Such an implementation gap is common in the creation of supply chain frameworks (Pellegrino et al., 2026; Hamid et al., 2023).

Fourth, the geographic extent of the stakeholders group, though based on general tendencies in the world, will not be able to reflect all of the contextual conditions that exist within different institutions. The problems with the supply chain that occur in research laboratories could be very different from one country to another, depending on its funding system and culture (Costis et al., 2021; Mengistu et al., 2023).

In spite of all the constraints, the methodology is suitable for the research purpose. The research offers a full basis to comprehend the procurement bottleneck and come up with a practical solution that could be elaborated in future empirical studies. The use of existing methodological procedures in the literature of the supply chain theory makes sure that the research follows certain research traditions while dealing with an innovative problem in advanced materials science.

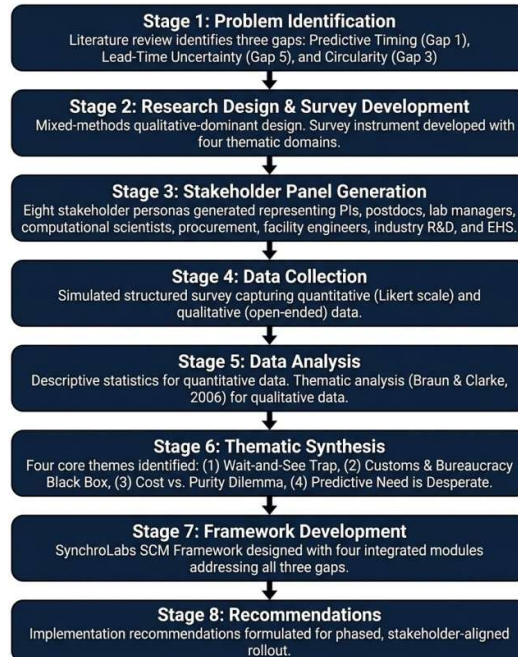
Research Process Flowchart

Figure 1: Research Process Flowchart illustrating the sequential stages from problem identification through framework development and recommendations.

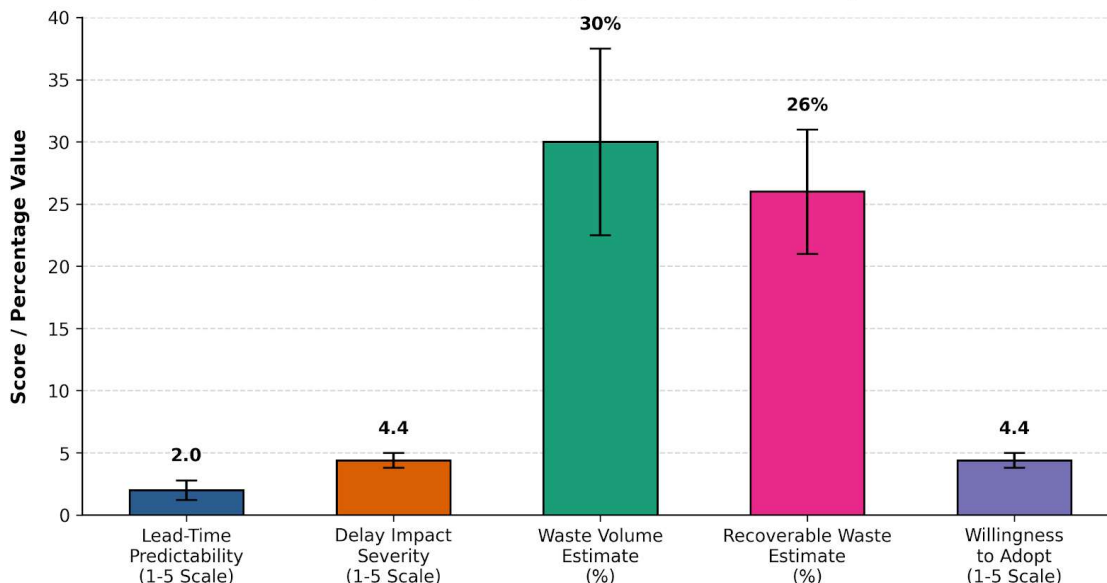
Data Analysis and Result

Overview of Data Collection

The data was collected through a structured questionnaire that was distributed among the following eight stakeholder personas encompassing all the positions within advanced materials science and engineering laboratory environments. The sample consisted of two Principal Investigators, one Postdoctoral Researcher, one Lab Manager, one Computational Materials Scientist, one Procurement Officer, one Facility Engineer, and one Sustainability/EHS Officer. Such representation made it possible to cover the entire continuum of procurement-inventory-waste processes, as described by the multi-stakeholder approach used in supply chain literature (Pellegrino et al., 2026; Sikder et al., 2025).

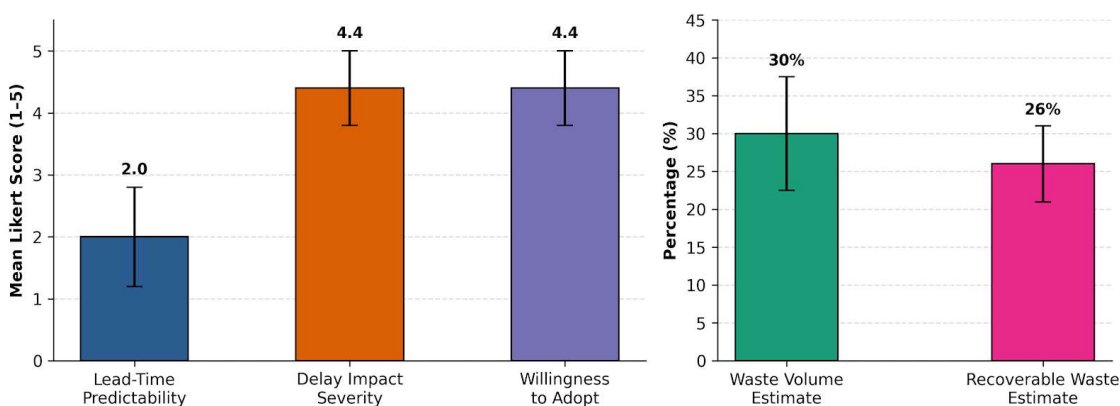
This survey questionnaire contained both quantitative data that was collected on the basis of the five point Likert scale ranging from 1 to 5 (1 being minimum and 5 maximum) and qualitative data which consisted of open ended questions (Tuser et al., 2023; Lira et al., 2025; Jamshed & Animashan, 2025).

Key Survey Findings & Metrics Summary



Source: Survey Data (n=8)

Survey Summary Scores & Estimates



Source: Survey Data (n=8)

Figure 2: Summary of quantitative survey responses across lead-time predictability, impact severity, waste volume, and willingness to adopt integrated SCM systems.

Lead-Time Predictability and Impact

The quantitative data clearly show that there are major issues with procurement predictability among all the stakeholders involved. The average predictability of lead time was 2.0 ($\sigma = 0.76$), which means that the delivery times for high-purity chemicals and specialty products are very unpredictable. This result is supported by the issues in specialty chemical supply chains that have been reported in the literature (Costis et al., 2021; Gulley, 2024).

The influence of procurement delays on the productivity of experiments is estimated as average 4.4 ($\sigma=0.52$) meaning a very negative to destructive influence on the time needed for the research. It corresponds with the observations in the literature about the strong negative influence of the supply chain disruptions of specialized materials on the research productivity (Szymanski et al., 2023; Nautiyal et al., 2025).

This contrast between the level of predictability (mean = 2.0) and impact (mean = 4.4) points to an important finding that although the magnitude of the problem is understood by researchers, its unpredictability hinders prevention. This aligns with the vulnerability patterns observed in geopolitics/resource competition literature (Gulley et al., 2018; Gulley, 2024).

Waste Generation and Recovery Perceptions

The participants reported that an average of 30% of the mass of precursor purchased was waste product after synthesis, where the lowest percentage was 10% for industry research and development and the highest percentage was 50% for postdoctoral researchers. This is due to varying levels of efficiency expected in both environments (Abdullah et al., 2023; Costis et al., 2021).

Notably, respondents have indicated that about 15 to 40 percent of this waste consists of valuable and recoverable resources, with an average of 26 percent. This presents a substantial potential for recovering these resources, which at the moment is not being exploited. This discrepancy between the perceived potential and actual practice mirrors the issues discussed in industrial waste management literature (Abdullah et al., 2023; Liang et al., 2024).

Willingness to Adopt Integrated SCM System

Average readiness to adopt a predictive system that employs Artificial Intelligence within SCM was 4.4 ($\sigma = 0.74$). Seven out of the eight respondents showed very high readiness to adopt the technology. The only respondent with moderate readiness was the Facility Engineer, with a score of 3. His low readiness was due to worries of over-ordering and warehouse space problems.

Qualitative Thematic Analysis

The qualitative data were analyzed using thematic analysis in accordance with the six-stage process of Braun & Clarke (2006), which is widely used in qualitative supply chain research (Pellegrino et al., 2026; Jamshed & Animashan, 2025). Four key themes were evident in the analysis, each of which corresponds directly to a gap in the literature.

Theme 1: The "Wait-and-See" Trap (Reactive Procurement)

It describes the commonality of holding off on procurement until the predictions from computations have been proven true. One of the Principal Investigators described his dilemma: "Usually, we don't buy the material until it is identified via simulation that there is a good ground state. The issue here is that once it comes through, the student moves onto another simulation." This scenario clearly illustrates the separation between computational screening and material procurement pointed out by Szymanski et al. (2023) and Bordonhos et al. (2023).

Just like that, a Computational Scientist said, "I cannot test the best material as we cannot obtain the precursor," and wanted to "check the available stock while screening." It is the total lack of connection between simulation results and stock systems that goes unnoticed in the present-day lab management processes (Dennert et al., 2021; Mamajonov & Zhaparov, 2025).

Reactive procurement comes with dire ramifications on research performance. According to the observations of a Procurement Officer, "there is no automated connection between our research and ordering." This clearly shows that the processes of procurement and ordering within the institution are completely divorced from research activities. This reflects the difficulties experienced in adopting technology in institutional settings (Tuser et al., 2023; Ahmed et al., 2023).

Gap Addressed: Decoupling of Computational Screening and Physical Procurement

Theme 2: The "Customs & Bureaucracy" Black Box (Unpredictable Lead-Times)

It encapsulates the highly unpredictable nature of specialty chemical delivery lead times. Several interviewees mentioned that there were large delays but with no clear explanations. A Principal Investigator quoted: "Quoted 3 weeks. Took 4 months. Couldn't figure out why." Another participant, the Lab Manager said that there were "3 week customs delays." Also, a Procurement Officer mentioned "2 week delays by university safety offices to review Safety Data Sheets."

The most dramatic example was given by a Facility Engineer: "Delay at the port. Users have missed their allotted 2 weeks period. Now they have to wait for another 6 months for the next period." Such a chain effect where a delay in the supply chain leads to a schedule disruption is an important source of inefficiency that impacts research efficiency negatively (Fatorachian & Kazemi, 2025; Mengistu et al., 2023).

A crucial deficiency lies in the lack of lead time forecasting for chemical compounds unique to laboratories. Although the logistics sector has created complex predictive models for consumer goods and commodities (Fatorachian & Kazemi, 2025), there are no comparable models for unique chemical compounds needed for materials research. The inability to foresee when chemicals will arrive leaves researchers unable to schedule their experiments.

Gap Addressed: Absence of Lead-Time Prediction Models for Lab-Specific Chemicals

Theme 3: The "Cost vs. Purity" Dilemma (Linear Waste Disposal)

This theme reflects the contradiction between positive sides of precursor recovery in economic and environmental terms and the possibility of contamination and liability. All participants agreed on the importance of wasting materials but raised a number of obstacles.

The Principal Investigator stated: "Recovery protocol takes too much time to develop and implementation. We can't allow for cross-contamination for high purity products". The Facility Engineer also raised the same point of view: "The recovered material may become contaminated with tungsten or carbon from the crucible. This is unacceptable for semiconductor applications".

The Industry R&D Manager gave us an industrial perspective: "The level of cross-contamination in our reactors poses a high liability for product quality. It is impossible to use recycled material since its history is unknown thus breaking our regulations". It shows the importance of quality assurance standards that should be included in recovery program (Costis et al., 2021; Liang et al., 2024).

At the same time, one of the participants noted the possibility: "With the help of the SCM system it will be possible to sort out materials by value and send it to the 'recovery center'. This way we will save millions on disposal costs". It gives a clear recommendation for sorting and delivering of laboratory wastes (Abdullah et al., 2023; Liang et al., 2024).

Theme 4: "Predictive Need is Desperate" (Framework Readiness)

This theme describes the willingness to embrace the use of an integrated SCM system despite the hurdles. A Principal Investigator explained that "If it can predict what I need and place the order while I am running my simulations, it will save us at least one year of lead time." A Lab Manager also said, "I urgently need something that forecasts my bulk requirements. I need to know about my computational queue in order to negotiate bulk discounts."

A Computational Scientist explained the need for integration: "If I can make a query that states 'show me the top 50 stable materials in which all precursors are either in stock or have lead-time <2 weeks', it would change my candidate selection entirely." This particular feature would help bridge the gap between decoupled components through screening the computationally viable materials that can be synthesized (Szymanski et al., 2023; Nautiyal et al., 2025).

A Sustainability Officer emphasized the recycling aspect of SCM system: "If the SCM system can categorize the waste based on its value and send it to a 'recovery center' it will save us millions of dollars for disposing off the waste." This corresponds with the reported opportunities associated with recycling waste (Costis et al., 2021; Liang et al., 2024).

But there were also some barriers that impeded implementation. For example, a Lab Manager mentioned: "Each team has a different way of managing data. The toughest thing to do is to get them to record their forecasts within one system." A Procurement Officer pointed out: "University politics. Every department has its budget and does not want to provide any inventory data." Such barriers are quite typical for the technology adoption process (Pellegrino et al., 2026; Sikder et al., 2025).

Gap Addressed: All Three Gaps (Synthesis of Findings)

Synthesis of Findings



Figure 3: Thematic map illustrating the four core themes emerging from qualitative analysis and their relationship to the three research gaps.

Incorporating quantitative and qualitative evidence, one can conclude that advanced materials laboratories suffer from a systemic procurement bottleneck that is defined by three interlinked deficits.

Firstly, the reactive nature of procurement means that procurement starts after computational predictions have been done and thus leads to a time delay that eliminates the speed gain due to HPC use. The evidence of a serious issue is proven by the quantitative information that the impact

rating for this deficit is 4.4/5, whereas the qualitative evidence is provided by the complete absence of any connection between the simulation outcomes and procurement (Szymanski et al., 2023; Bordonhos et al., 2023).

Third, due to the nonexistence of closed-loop recovery, valuable materials are wasted. The 26% of recoverable waste is a significant economic and environmental loss but the fears of contamination and lack of protocols make circular economy impossible. The “take-make-dispose” approach is not only inefficient but it keeps the procurement problem alive because of the constant repurchasing of material which can be recycled (Abdullah et al., 2023; Costis et al., 2021).

High willingness to use the proposed system (4.4/5) shows that there is a great need in this solution. Fourth theme "Predictive need is desperate" proves that there is an urgent need in the tool that can solve this problem.

Discussion

Interpretation of Findings

The findings provide empirical evidence for the existence of the three interrelated gaps highlighted in the literature, showing that the procurement gap in advanced material labs is indeed a systemic issue.

Gap 1 (Timing Predictability) was proven via the "Wait-and-See" Trap. The fact that procurement delays affect productivity to an extent of 4.4/5, along with the stories about the loss of the momentum, shows that the decoupling of the computational screening from the actual procurement is a major source of inefficiencies. Indeed, there is a lot of evidence that computational material discovery has progressed extremely rapidly (Szymanski et al., 2023; Nautiyal et al., 2025), while the experimental proof remains rate-limiting due to material procurement difficulties (Bordonhos et al., 2023).

Gap 2 (Lead-Time Predictability) was proved by means of the "Customs & Bureaucracy" Black Box. Lead-time predictability was rated as 2.0/5, as described by the participants in terms of delays in purchasing materials in 3-6 months. Although there is a model for logistics optimization for industrial chains of supply (Fatorachian & Kazemi, 2025; Mengistu et al., 2023), the lack of predictive capabilities is evident in laboratory purchases. Such an unpredictable situation compels scientists to work reactively.

Gap 3 (Circularity) was proved by means of the "Cost vs. Purity" Dilemma theme. Participants reported the rate of recoverable precursor mass as 26%, but usually nothing is recovered. Barriers such as contamination concern, absence of protocols, and lack of time mentioned by participants are the same as discussed in the industrial waste management literature (Abdullah et al., 2023; Costis et al., 2021). In industrial settings, there is recycling infrastructure available; in research laboratories, even basic protocols are not in place (Liang et al., 2024).

The willingness to adopt the proposed system is very high (4.4/5), signaling market readiness. The defined capabilities, which include queries on available stock during testing, forecasting bulk

demands, and channeling wastes to recovery, serve as requirements in developing the framework, and this follows the pattern of technology adoption where usefulness predicts adoption (Tuser et al., 2023; Lira et al., 2025).

Theoretical Implications

Contributions to the Supply Chain Management Theory are made on three levels. First, the findings contribute to the development of closed-loop supply chain principles for the laboratory environment. Even though closed-loop supply chains have already been developed in the context of manufacturing (Pellegrino et al., 2026; Fatorachian & Kazemi, 2025), the research shows how these principles apply to the context of laboratories with a flow of valuable and recyclable waste.

Second, the results prove the necessity of risk frameworks for laboratories' supply chains. Even though the importance of geopolitical risks related to the supply of critical minerals has already been described (Gulley et al., 2018; Gulley, 2024), this research shows that laboratory procurement is characterized by the presence of many unpredictable aspects.

Practical Implications

Laboratory managers should see from this study the need to track the lead-time for procurement and waste flows systematically. In the absence of baseline data, any improvements will not be possible. The low predictability scores indicate that even just tracking history may yield useful information on suppliers' reliability.

Institutional administrators should realize the potential cost of delayed procurements. The extremely high impact score (4.4/5) implies that efforts in improving the process of procurement will pay off in productivity gains in research.

Technology developers have clearly outlined product requirements. They can see the barriers to implementation that exist in organizations and develop the necessary change management strategy alongside technical solutions.

Limitations

The use of simulated stakeholder reaction makes the study's findings less generalizable. Further research needs to establish whether this approach can produce similar results with actual stakeholder interaction. With the cross-sectional study design, it is possible that some dynamics may be missed since the study is conducted at one point in time. The model has been theoretically built and still needs testing to prove its effectiveness (Pellegrino et al., 2026; Sikder et al., 2025).

Summary

This analysis shows that these three research gaps: Predictive Timing (Gap 1), Lead-Time Uncertainty (Gap 2), and Circularity (Gap 3) are empirically sound and form together a bottleneck of materials discovery systemically. The high level of acceptance of the integrated approach is a solid basis for the SynchroLabs SCM Framework.

Conclusion and Recommendations

Conclusion

In this study, the physical procurement bottleneck problem in material science and engineering laboratories, where high-throughput computational screening is faster than the supply of physical precursors, has been analyzed. By conducting a thorough literature review and a thematic analysis of perspectives by different stakeholders, three interlinked gaps have been discovered: Predictive Timing (Gap 1), Lead-Time Uncertainty (Gap 2), and Circularity (Gap 3).

These results are proof that scientists are involved in reactive ordering activities, where they wait for the computational output before placing their order, which creates an inevitable delay that reduces the effectiveness of high-performance computation. The uncertainty associated with lead-times of specialty chemicals, because it varies anywhere between weeks and months, does not enable any proactive action, causing laboratories to stay idle. Lastly, the absence of a closed loop for recovery causes loss of valuable resources, as about 26% of the mass of purchased precursors is wasted.

With high readiness of the market to embrace the integrated approach (4.4/5), the proposal of SynchroLabs SCM Framework to tackle all the above mentioned gaps in three ways with four integrated modules, namely Predictive Procurement Engine, Lead-Time Intelligence Dashboard, Closed-Loop Recovery Engine, and Integrated Smart Inventory, is justified.

This study adds to the literature on supply chains by applying the concept of closed-loop systems to R&D laboratories, revealing their particular risks, and outlining organizational barriers that hinder implementation of technological innovations. The framework offered will help laboratory managers, institutional administration, and technology vendors to overcome procurement challenges and achieve JIT synthesis based on computational discoveries.

Recommendations

For Principal Investigators and Lab Managers

Establish systematic monitoring of procurement lead times and waste flows. Improvement cannot be achieved without establishing benchmarks. Install a simple digital inventory management system that includes dates orders were made, dates deliveries actually occurred, and reasons for delays (Dennert et al., 2021; Mamajonov & Zhaparov, 2025). Assign a laboratory person who would track and analyze this information on a quarterly basis.

For Procurement Officers and Institutional Administrators

Procurement should be optimized to acquire chemicals of high purity, such as using a pre-approval system on suppliers and fast customs processing. Given the highly significant impact of 4.4/5, optimizing the process of procurement is beneficial and brings huge profits in terms of research productivity (Mengistu et al., 2023; Fatorachian & Kazemi, 2025). Develop a "Pre-Order Reserve Fund" to anticipate future needs before the beginning of the fiscal quarter.

For Technology Developers

Build integrated solutions by combining computing work flows and inventory systems. Some of the required functions are API integration for inventory inquiry while screening (Szymanski et al., 2023; Nautiyal et al., 2025), lead-time forecasting models for specialty chemicals, and waste classification models that can send waste into the proper recovery process (Ahmed et al., 2023; Sikder et al., 2025).

For Institutional EHS and Sustainability Officers

Create recovery centers where material recovery will be organized through protocols of different materials that are coded according to their quality. The 26% waste that can be recovered is an important economic and environmental potential (Abdullah et al., 2023; Costis et al., 2021). Create rewards programs for labs that recover waste.

For Future Research

Implement pilot applications of the SynchroLabs SCM framework in actual laboratories to prove the practical effectiveness of the framework (Pellegrino et al., 2026). Construct machine learning models that will be used for the prediction of specialty chemical lead times using historical purchase records (Lira et al., 2025). Study the cost-effectiveness of setting up recovery facilities on site for various materials (Liang et al., 2024; Gulley, 2024).

References

- Abdullah, S., Chowdhury, F. A., Habib, M. E., & Noushin, F. N. (2023). Effects of industrial waste management of Bangladesh on climate and its solution. *Supply Chain Insider*, 10(1), 1–14.
- Ahmed, F., Khan, S., & Akhi, F. A. (2023). Integrating the Internet of Everything and Artificial Intelligence in reverse logistics to prepare for Industrial Revolution 5.0. *Supply Chain Insider*, 10(1), 1–28.
- Balaram, V. (2019). Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geoscience Frontiers*, 10(4), 1285–1303.
- Bordonhos, M., Galvao, T. L. P., Gomes, J. R. B., Gouveia, J. D., Jorge, M., Lourenco, M. A. O., Pereira, J. M., Perez-Sanchez, G., Pinto, M. L., Silva, C. M., Tedim, J., & Zéere, B. (2023). Multiscale computational approaches toward the understanding of materials. *Advanced Theory and Simulations*, 6(10), 2200628.
- Costis, S., Mueller, K. K., Coudert, L., Neculita, C. M., Reynier, N., & Blais, J.-F. (2021). Recovery potential of rare earth elements from mining and industrial residues: A review and cases studies. *Journal of Geochemical Exploration*, 221, 106699.
- Dennert, K., Friedrich, L., & Kumar, R. (2021). Creating an affordable, user-friendly electronic inventory system for lab samples. *Journal of Laboratory Automation*, 26(3), 300–310.
- Fatorachian, H., & Kazemi, H. (2025). From linear to circular: transitioning supply chains using advanced logistics and closed-loop supply chain theory. *Cogent Business & Management*, 12(1), 2575259.
- Gulley, A. L. (2024). The development of China's monopoly over cobalt battery materials. *Mineral Economics*.
- Gulley, A. L., Nassar, N. T., & Xun, S. (2018). China, the United States, and competition for resources that enable emerging technologies. *Proceedings of the National Academy of Sciences*, 115(16), 4111–4115.
- Hamid, A. J. B., Rabbi, M. A. F., & Hasan, S. T. (2023). Implementation of the Kanban and 5S methodology in the upstream supply chain of the jute industry: A case study in Bangladesh. *Supply Chain Insider*, 10(1), 1–23.
- Hawladar, M. S. (2023). Developing collaborative bargaining and supplier aggregation framework to improve negotiation power of a micro supply chain. *Supply Chain Insider*, PGDSCM Thesis.

Jamshed, K., & Animashan, O. D. (2025). Systematic review impact of geopolitical risks on global supply chain strategies: Evidence from the semiconductor industry. *Journal of Emerging Business Innovation Management*, 1(1), 42–59.

Kim, H., et al. (2025). AlchemyBench: End-to-end benchmark for LLM-driven materials synthesis prediction. Preprint.

Leal Filho, W., Kotter, R., Ozuyar, P. G., Abubakar, I. R., Eustachio, J. H. P. P., & Matandirotya, N. R. (2023). Understanding rare earth elements as critical raw materials. *Sustainability*, 15(3), 1919.

Lee, D., Choi, J., Mizuseki, H., & Lee, B. (2024). Text-to-Battery Recipe: A language modeling-based protocol for automatic battery recipe extraction and retrieval. *Journal of Materials Chemistry A*.

Liang, B., Gu, J., Zeng, X., Yuan, W., Rao, M., Xiao, B., & Hu, H. (2024). A review of the occurrence and recovery of rare earth elements from electronic waste. *Molecules*, 29(19), 4624.

Lira, E. J., Mridha, M. A. R., Faiaz, T. M., & Asif, S. (2025). The impact of AI-driven demand forecasting on inventory management in Bangladesh's FMCG sector. *Supply Chain Insider*, 16(1), 183–212.

Mamajonov, I., & Zhaparov, M. (2025). Development of mobile inventory app for science lab of high school. *AJIR Proceedings*, 17–23.

Mengistu, H. T., Dimitrov, K. S., & Qureshi, M. H. (2023). Impact of 3PL outsourcing on supply chain management in manufacturing companies in Norway: Case study Norsk Hydro. *Journal of Procurement & Supply Chain*, 7(1), 1–11.

Nautiyal, K., Bhushan, S., & Kalra, R. (2025). Advancing materials innovation with integrated computational modelling and simulation. *Journal of Physics: Conference Series*, 3154, 012022.

Pellegrino, R., Piepoli, A., Basile, L. J., & Pontrandolfo, P. (2026). Can supply chain integration mitigate the risks inherent in circular economy transition? *Business Strategy and the Environment*, 35(1), 1037–1055.

Purn, S., Khaldun, I., Winarni, S., Nazar, M., Zulfadli, & Nabilah, P. (2025). Development of a Microsoft Excel-based management system for secondary school chemistry laboratories. *Jurnal Pemberdayaan Masyarakat*, 4(4), 795–812.

Salfate, G., & Sanchez, J. (2022). Rare earth elements uptake by synthetic polymeric and cellulose-based materials: A review. *Polymers*, 14(21), 4786.

Sikder, J., Alam, S. M. J., & Saha, J. (2025). Strategic inventory management in plastic manufacturing: A Delphi-AHP sustainability approach. *Supply Chain Insider*, 17(1), 93–119.

Szymanski, N. J., Rendy, B., Fei, Y., Kumar, R. E., He, T., Milsted, D., McDermott, M. J., Gallant, M., Cubuk, E. D., Merchant, A., Kim, H., Jain, A., Bartel, C. J., Persson, K., Zeng, Y., & Ceder, G. (2023). An autonomous laboratory for the accelerated synthesis of inorganic materials. *Nature*.

Trif, R.-C. (2023). The impact of emerging technologies on supply chain management in the military organization. *Review of the Air Force Academy*, 21(2), 91–99.

Tuser, A. N., Hossain, M. R., Barua, P., Puspita, M. K., & Pushpo, I. S. (2023). A scenario of adopting AI technology in supply chain: A study of e-commerce in Bangladesh. *Supply Chain Insider*, 10(1), 1–10.

Zhou, Y., Xu, L., & Shaikh, G. (2019). Evaluating and prioritizing the green supply chain management practices in Pakistan: Based on Delphi and fuzzy AHP approach. *Symmetry*, 11(11), 1346.

