A Scalable, Work-Integrated E-Learning Model for Rapid Upskilling in Biomanufacturing

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Abstract: Africa faces significant challenges in developing a skilled biomanufacturing workforce, including rapid upskilling needs, limited access to high-quality training, and diverse learner backgrounds. These constraints require scalable, adaptable e-learning solutions that align with industry and regulatory demands, particularly for working professionals pursuing continuing education. This paper presents an inclusive, scalable online pedagogical model grounded in constructivist learning theory. Using a flipped-classroom approach, it combines asynchronous, self-paced learning with synchronous, application-oriented sessions within a competency-based framework. Learners engage with multimedia-rich content prior to live online sessions, enabling synchronous time to focus on higher-order skills such as problem-solving, discussion, and contextual application. Gamification and Problem-Based Learning (PBL) support engagement, critical thinking, and collaborative knowledge construction, while feedback from Subject Matter Experts (SMEs) ensures real-time validation of learning. The curriculum is organised into units with clear learning outcomes, aligned with Bloom's taxonomy and supported by question banks to ensure constructive alignment. Formative and summative assessments enable both mastery learning and performance evaluation. Delivered via a digital ecosystem centred on Canvas LMS and interoperable content authoring tools, the model supports scalability, analytics, accessibility, a Bring Your Own Device (BYOD) approach, and multilingual adaptability, facilitating inclusive participation across diverse geographic and professional contexts. Implemented across industrial and higher-education (HE) settings, the model was associated with positive feedback among learners. Its modular and reusable design offers a flexible, transferable approach to e-learning that supports workforce development across disciplines and environments, including resource-limited settings.

Keywords: Flipped-Classroom Model, Problem-Based Learning, Constructivist Pedagogy, Gamification, Biomanufacturing Workforce Development, Work-Integrated Learning.

1. Introduction

In the pharmaceutical and biomanufacturing sectors, professional training is undergoing a major transformation driven by increasing global demand for a skilled workforce, rapid technological advancement, and evolving regulatory expectations. Across the sector, there is growing recognition of the need for workforce development models that support timely, scalable, and competency-based education and training aligned with healthcare and industry priorities (International Pharmaceutical Federation, 2017).

The European biomanufacturing and life sciences sectors are experiencing rapid expansion alongside increasing concerns regarding shortages of appropriately skilled personnel. Recent European Commission and industry reports identify workforce capacity and specialised technical expertise as major constraints affecting the continued growth of biotechnology and biomanufacturing industries in Europe (European Commission, 2024; Work in Health Foundation, 2024). These challenges are further amplified in low- and middle-income regions, particularly in Africa, where the development of local pharmaceutical manufacturing capacity has become a strategic public health priority. The African Union has established a target to locally manufacture 60% of vaccines used on the continent by 2040, requiring substantial expansion of the biomanufacturing workforce (Mynhardt et al., 2024). Current estimates suggest that the vaccine manufacturing workforce will need to increase from approximately 2,000–3,000 professionals to between 9,000 and 14,000 by 2040 (Institut Pasteur de Dakar (IPD), Africa CDC and SAMRC, 2023).

Despite this growing demand, existing training ecosystems face structural limitations. Many programmes remain small-scale and prioritise theoretical knowledge over applied competencies, reducing learners' preparedness for operational roles in highly regulated manufacturing environments. Workplace-based learning and continuing professional development opportunities remain insufficient, while face-to-face delivery limits accessibility and scalability for geographically distributed and professionally active learners. As a result, organisations often rely on fragmented internal training systems or external providers that may not support sustainable long-term workforce development (IPD, Africa CDC and SAMRC, 2023).

This paper presents a scalable, work-integrated e-learning model developed to address these challenges within the context of biomanufacturing workforce development. The model originated from a workforce development initiative supporting the expansion of biomanufacturing operations in Africa. It was designed to provide a flexible training solution for personnel with heterogeneous educational and professional backgrounds while maintaining alignment with scientific, industrial, and regulatory requirements. To address these limitations, the instructional model was structured around three interconnected objectives: scalability across geographically distributed learners; compatibility with full-time professional responsibilities; and competency-oriented learning aligned with operational practice.

The model was not conceived as a replacement for practical laboratory or workplace training, which remains essential in biomanufacturing contexts, but rather as a complementary digital learning layer intended to accelerate theoretical preparation, process understanding, and operational readiness prior to workplace integration. The model combines asynchronous self-paced learning, synchronous collaborative activities, multimedia resources, and competency-aligned assessment within an integrated digital learning ecosystem. The instructional design was informed primarily by constructivist learning theory and operationalised through a flipped-classroom structure supported by Problem-Based Learning (PBL) and gamification strategies. These approaches were selected to support active participation, learner engagement, collaborative knowledge construction, and the application of learning to authentic professional contexts.

This paper, therefore, contributes to current discussions on scalable online professional education by presenting a transferable instructional design model for workforce development in resource-constrained and highly regulated environments.

2. Pedagogical Framework

2.1 Constructivist Learning Theory

Constructivism is a major framework for adult and lifelong learning because it views learning as an active process in which individuals construct knowledge through experience, reflection, social interaction, and authentic situations. Learners connect new information with prior knowledge and practical experience, while instructors primarily act as facilitators who support discussion, knowledge sharing, and the application of learning in workplace contexts. However, the successful implementation of constructivist learning environments in industrial settings may require appropriate pedagogical support and instructional design to develop authentic, learner-centred, and collaborative activities, particularly in technology-supported or online environments (Bada, 2015; Chuang, 2021; Gentile et al., 2022; Mohammed and Kinyo, 2020).

2.2 Flipped Classroom Approach

The flipped classroom is a learner-centred teaching approach in which instructional content is studied before class, while synchronous sessions focus on discussion, collaboration, and problem-solving. Strongly aligned with constructivist principles, this model promotes self-directed and active learning (Seifert, 2023; Akti Aslan, 2022).

Research generally indicates that flipped classroom approaches can improve student participation, motivation, interaction, and problem-solving skills, and engagement with educational content (Cuetos, 2023; Akti Aslan, 2022). However, evidence regarding learning achievement is less consistent. For example, Akti Aslan (2022) reported improvement in self-regulation and interaction, but no significant effect on academic achievement, suggesting that simply relocating content outside synchronous sessions is insufficient to guarantee improved learning achievement. Conversely, Thai et al. (2020) found significantly higher learning performance when additional feedback was incorporated into the online preparatory phase, indicating that the effectiveness of flipped learning may depend less on the “flipped” structure itself than on the quality of instructional support embedded within it. In professional training, flipped learning enables employees to complete self-paced preparation before participating in practical sessions focused on case studies and real-world applications. Its effectiveness, however, depends on learner motivation, self-directed learning skills, and clear instructional support (Gentile et al., 2022).

2.3 Problem-Based Learning Integration

PBL is a learner-centred approach in which learners acquire knowledge and skills by analysing real-world problems. Similar to constructivist learning theory and flipped classroom approaches, PBL emphasises

collaboration, inquiry, and application of knowledge in authentic contexts, while instructors act primarily as facilitators (Zeng and Ruannakarn, 2023; Stegeager et al., 2013; Lopez Brown, 2017).

Research has shown that PBL can improve critical thinking, problem-solving abilities, learner engagement, and the transfer of learning to practical situations compared with traditional lecture-based teaching (O'Brien and Hamburg, 2013; Zeng and Ruannakarn, 2023; Stegeager et al., 2013). This makes PBL relevant to professional training, although successful implementation requires authentic case design, appropriate facilitation, and sufficient learner support (O'Brien and Hamburg, 2013; Stegeager et al., 2013).

2.4 Gamification

Although constructivist, flipped classroom, and problem-based approaches support active learning, maintaining learner engagement remains a major challenge in online and workplace education. Gamification, therefore, provides a complementary strategy to increase motivation, participation, and interaction. Gamification refers to the integration of game elements into non-game learning environments. In e-learning, gamification has been increasingly adopted because online learning systems often suffer from low engagement and high dropout rates (Khaldi et al., 2023). Common elements include points, badges, and leaderboards, while more advanced approaches incorporate storytelling, role-play, challenges, and collaborative activities (Khaldi et al., 2023).

Research shows that gamification can positively influence learning outcomes, motivation, collaboration, participation, and learner enjoyment across different educational settings (Diaz and Estoque-Loñez, 2024; Su et al., 2025). However, these findings should be interpreted cautiously, as different game elements may influence different aspects of learning and engagement. Among the various gamified applications evaluated in educational research, Kahoot demonstrated one of the largest positive effects on learner engagement and academic performance (Diaz and Estoque-Loñez, 2024). It is worth noting that Khaldi et al. (2023) identified a gap between gamification theory and practice, with many applied studies lacking a clear theoretical rationale for selecting and combining particular game elements, while many design approaches remain insufficiently validated. Therefore, the effectiveness of gamification should be considered in relation to the educational context, learner characteristics and intended learning outcomes.

2.5 Cognitive Learning Strategies

In addition to active and learner-centred pedagogies, effective professional training requires strategies that support long-term retention of essential knowledge. Cognitive learning strategies support durable learning by encouraging learners to actively engage with content rather than passively review information. Retrieval practice, in particular, has been shown to be a universally effective learning strategy across different learner profiles and cognitive abilities (Bertilsson et al., 2021). Practical tools for cognitive learning strategies, such as flashcards or formative quizzes, can effectively promote active recall, spaced repetition, and self-assessment. A recent study found that students were highly adherent to flashcard initiatives and that increased flashcard use was associated with improved grades (Santos-Ferreira et al., 2024).

Collectively, the literature supports the integration of constructivist, flipped, problem-based, gamified and cognitive learning strategies; however, the evidence does not suggest that any single approach is universally effective. Rather, learning outcomes appear to depend on how these approaches are designed, facilitated, and aligned with instructional objectives and the learning context. This is particularly relevant when translating evidence predominantly derived from academic settings to professional and industrial training environments, where learners must balance training with workplace responsibilities and apply acquired knowledge to operational practice.

3. E-Learning Model Design

3.1 Content Development

The e-learning content was developed by the instructors through a structured co-design process involving Subject Matter Experts (SMEs) from diverse disciplinary and professional backgrounds, including industry specialists and external experts. SMEs contributed iteratively to the development process, providing feedback on scientific accuracy and industrial relevance.

The curriculum comprised five modules covering foundational scientific concepts (M1 and M2), microbiological principles (M3), biomanufacturing processes (M4), and quality control (M5). The present study focuses on the

first three preparatory modules (M1–M3), which were designed to establish a shared foundational knowledge base prior to process-specific training. These modules represented the most scalable and transferable components of the programme and were therefore selected for analysis. The overall programme received external accreditation and comprised 12 ECTS.

The model operationalised the pedagogical framework through a modular structure supporting progressive knowledge acquisition, learner autonomy, and applied learning. The structure was designed to accommodate diverse learner profiles while maintaining alignment with scientific, industrial, and regulatory requirements.

3.2 Technological Environment

The instructional model was implemented through an integrated digital learning ecosystem centred on Canvas LMS and supported by complementary tools including Articulate Rise, BioRender, Microsoft Teams, Kahoot, and Quizlet. The technological environment was designed to support multimodal content delivery, collaborative interaction, formative assessment, and scalable online participation across geographically distributed learners.

Canvas was selected as the LMS because it supports integration of multimedia resources, simulations, SCORM packages, H5P activities, and third-party learning tools within a single environment, reducing cognitive disruption and maintaining continuity throughout the learning process. In addition, Canvas offered intuitive navigation, integrated assessment and feedback tools, discussion forums, progress tracking, and engagement analytics.

These features supported scalable delivery while facilitating a Bring Your Own Device (BYOD) approach compatible with diverse technological contexts. Compatibility with multimedia and interactive resources also supported the implementation of competency-based and learner-centred training approaches in biomanufacturing education.

3.3 Course Architecture

The course architecture was designed to operationalise constructivist and flipped-classroom principles by integrating asynchronous and synchronous active-learning activities. Each module began with an online kick-off session that introduced the module structure, assessment strategy, and expectations, while supporting early learner interaction.

All learning materials were made available from the beginning of the module. Although learners were free to navigate the content at their own pace and according to their preferences, a sequential progression was recommended to support gradual knowledge development and competency acquisition. Interactivity was embedded throughout the modules to support engagement, reflection, and application of knowledge. Within each module, the curriculum was organised into units that progressed from foundational concepts to more advanced, applied topics (Figure 1, left).

Most units began with a discussion forum designed as a PBL activity (Figure 1, top right). PBL activities were intentionally non-graded to encourage open participation and exploratory thinking. By introducing authentic professional scenarios before formal instruction, these activities aimed to stimulate early reflection, contextual reasoning, and asynchronous peer interaction.

Learning materials were delivered through multiple complementary formats, including instructor-developed videos, curated external video resources, written explanatory materials, and interactive digital content. The use of diverse resource types aimed to accommodate varying learning preferences, support self-paced engagement, and provide multiple entry points for understanding complex scientific and technical concepts. Learning materials incorporated multilayered visual and interactive resources, developed using BioRender and Articulate Rise, to support engagement and accommodate learners with diverse backgrounds, allowing them to explore content at varying depths while reaching common competency goals. Introductory visual summaries provided accessible entry points to the content, while embedded exploratory elements, including hotspots (Figure 1, bottom right), expandable sections, and external references, allowed learners to progressively engage with increasingly advanced information as their learning needs evolved.

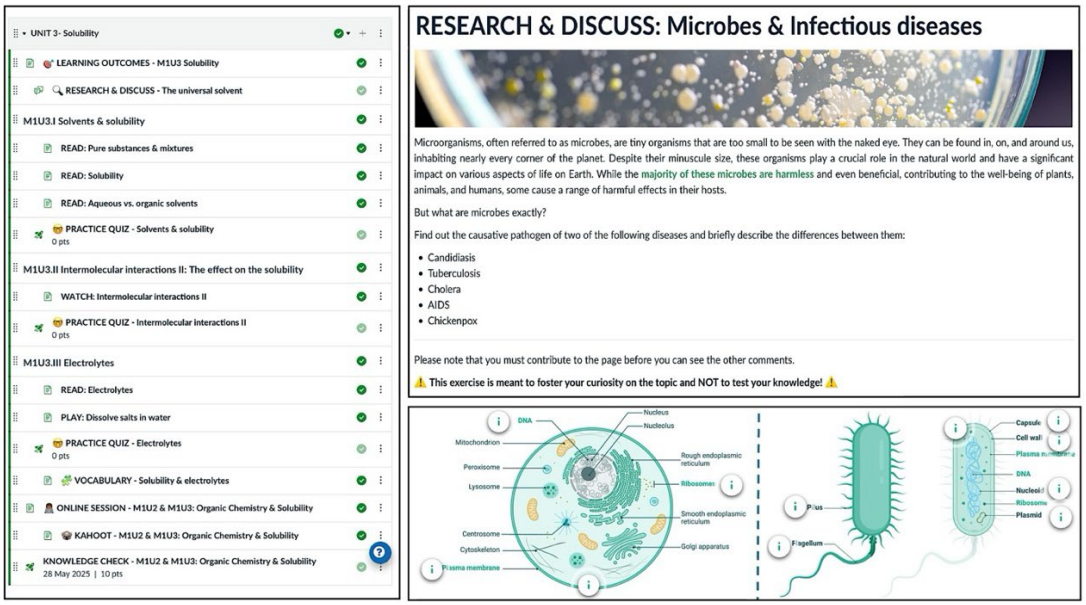


Figure 1: Left: Example of the structure of a unit within a module. Top right: Example of a PBL activity in a discussion forum on Canvas. Bottom right: Example of an interactive picture used in a module.

The learning outcomes were explicitly communicated at the beginning of each unit to support transparency and self-regulated learning. Formative assessment activities were integrated throughout the modules to support continuous self-evaluation and knowledge consolidation prior to summative assessment.

Each unit included flashcard sets that could be used in different game-based study modes (Figure 2). Additional learner-responsive knowledge-check activities were incorporated to reinforce terminology and conceptual understanding (Figure 3).

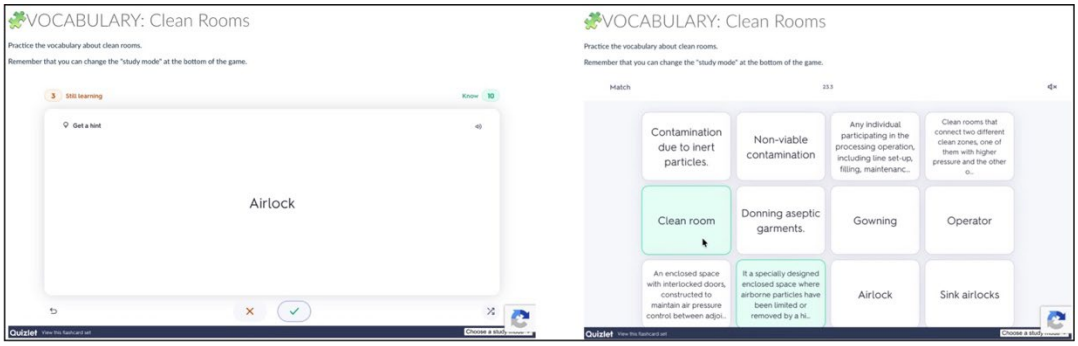


Figure 2: Examples of study modes for vocabulary activities used in the modules.

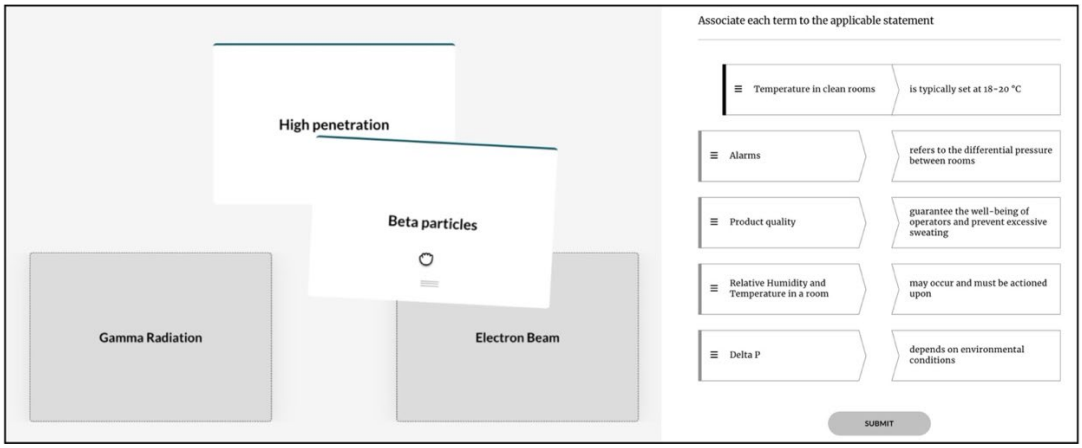


Figure 3: Examples of knowledge-check interactive activities used as formative assessment in the modules.

Simulations and scenario-based activities were incorporated where appropriate to support procedural understanding and application-oriented learning in contexts that would otherwise require laboratory or manufacturing facilities (Figure 4). Such activities were particularly valuable in biomanufacturing contexts, where visualisation, procedural understanding, and process awareness were essential for operational readiness.



Figure 4: Left: Simulation of sterile gowning procedures (NCBioNetwork, 2023). Right: Simulation of the solubility of salts (PhET Interactive Simulations, 2026).

In addition to asynchronous learning activities, regular synchronous online sessions were scheduled throughout each module. These sessions generally covered one or two units and lasted between 1.5 and 2 hours. Learners were encouraged to complete all asynchronous learning materials before attending the corresponding online sessions. These sessions focused on clarifying complex concepts, checking achievement of learning outcomes, elaborating on collaborative reflection, and discussing applied case studies. Kahoot quizzes were used as gamified discussion activities rather than formal assessment tools, promoting participation and peer interaction. Instructors used quiz questions as prompts for discussion and collaborative reflection and continuously encouraged learners to share questions and professional experiences to leverage the diversity of the learner groups. SMEs also participated in selected sessions to support discussion of technical topics and operational case studies.

Collectively, asynchronous self-paced learning, synchronous collaborative activities, multimedia resources, simulations, and gamified interactions created a multimodal active-learning environment in which learners continuously engaged with content, peers, and instructors, and applied their learning to professional scenarios.

From a delivery perspective, the model supported flexible implementation formats adapted to organisational constraints and learner profiles. The part-time format allocated approximately two weeks per module, with an average daily workload of four hours, enabling learners to combine training with their professional responsibilities. An intensive full-time format, comprising one week per module and an estimated daily workload of eight hours, was also proposed to support rapid onboarding and dedicated upskilling. Together, these formats enabled the model to be implemented across different workforce-development scenarios.

3.4 Quiz-Based Assessment Strategy

Formal evaluation was implemented through a structured quiz-based assessment system delivered within Canvas LMS. The assessment architecture was designed by the instructors to support competency-oriented learning, constructive alignment, retrieval practice, and scalable online delivery.

The training was organised into units defined by explicit learning outcomes developed according to the SMART framework and aligned with Bloom's taxonomy. To support alignment among learning objectives and assessment tasks, a dedicated question bank was developed for each learning outcome. Each question bank contained a set of questions targeting the same competency level and cognitive domain associated with the corresponding learning outcome. These question banks enabled consistency across assessments while allowing controlled variability through quiz randomisation mechanisms within Canvas. Assessment activities included multiple-choice and multiple-answer questions, matching exercises, fill-in-the-gap, categorisation tasks, ordering activities, and applied problem-solving exercises. The assessment model combined formative and summative components to support continuous learning and competency evaluation.

Formative assessment quizzes, termed "Practice Quizzes", were distributed throughout each unit to support self-regulated learning, retrieval practice, and iterative knowledge reinforcement. These quizzes contained 4–8

randomly selected questions drawn from the corresponding learning outcome-aligned question banks. Learners were allowed unlimited attempts without time limits, and immediate feedback was provided upon submission.

Summative evaluation was implemented through unit-level "Knowledge Checks" and a cumulative "Final Exam", both derived from the same learning outcome-aligned question bank structure as the Practice Quizzes. The Knowledge Checks and Final Exam were conducted within set time limits and allowed only a limited number of attempts. The pass mark for all summative assessments was set to 50%. Knowledge Checks typically contributed 8–10% each to the final module grade, while the Final Exam accounted for 60% of the total evaluation.

This approach enabled standardised evaluation processes, efficient deployment across multiple course iterations, and competency-aligned assessment with minimal reliance on synchronous examiner involvement. In addition, automated grading and integrated learning analytics enabled continuous monitoring of progress and facilitated the early identification of learners who required additional support.

Overall, the assessment strategy was designed to progressively transition learners from low-stakes knowledge reinforcement towards cumulative competency validation while supporting scalability and consistency within and across cohorts.

4. Methods

The educational programme was developed and delivered as part of routine teaching and professional education activities and was not originally designed as a research study. No learners were prospectively recruited for research purposes. The present study therefore adopted a retrospective case-study approach to describe the instructional design, its application across different educational settings, and learners' perceptions of their experiences.

Learner perceptions were evaluated using anonymous EvaSys (evasys GmbH, Lüneburg, Germany) questionnaires administered after each module. Closed-response items assessed perceived achievement of learning outcomes, quiz–learning outcome alignment, module organisation and navigation, learner interest, adequacy of time allocation, and the contribution of synchronous sessions to consolidating asynchronous learning. Items were rated on a five-point Likert scale from 1 (strongly disagree) to 5 (strongly agree). Open-ended questions addressed module organisation, learning-resource preferences, and the teaching approach. Industrial and higher-education (HE) data were analysed separately. As questionnaires were administered after each module, responses represent module-level responses rather than unique learners. Common closed-response items were pooled within each setting and reported as means, standard deviations (SD), and positive responses (ratings 4–5). Pooled estimates were weighted by module-level response counts.

Open-ended responses were analysed using descriptive qualitative content analysis. A substantive response was defined as an interpretable response relevant to the question asked. Non-answers (e.g., "N/A"), uninterpretable responses, and off-topic responses were excluded, whereas explicit statements of no improvement or disliked aspects were retained as substantive responses. Responses were analysed separately for each open-ended question, including paired prompts exploring positively and less positively perceived aspects of module organisation, learning resources, and the teaching approach. Responses expressing similar ideas within each question were grouped into descriptive categories, and multiple categories could be assigned to a single response. The analysis was AI-assisted using ChatGPT (OpenAI, GPT-5.6 Sol) to organise responses, propose descriptive codes and categories, and identify ambiguous or overlapping classifications. Outputs were reviewed against the original responses, with ambiguous classifications manually reviewed and final coding decisions made under author oversight. Frequencies and percentages were calculated using substantive responses to each question as the denominator; percentages were not mutually exclusive because multiple coding was permitted.

5. Results

5.1 Learner Feedback Dataset

The model was implemented across four training deliveries in two educational settings: three industrial deliveries accounting for 120 module completions and one higher-education (HE) delivery accounting for 142 module completions across three preparatory modules (M1–M3). This resulted in 12 module implementations and corresponding evaluations. Anonymous learner feedback was collected at the end of each module through EvaSys by our institution as part of routine quality-assurance procedures. Across the industrial deliveries, 62 questionnaire responses were available from 120 module completions, representing a module-level response

rate of 51.7%. In the HE delivery, 85 responses were available from 142 module completions, representing a module-level response rate of 59.9%. Because feedback was collected after each module, these values represent module-level responses rather than unique respondents. The open-ended items generated 858 item-level responses across all questionnaire prompts—rather than responses from 858 individual learners—comprising 342 from the industrial implementations and 516 from the HE implementation. After blank, uninterpretable and off-topic entries were excluded, 751 responses were retained for qualitative content analysis. Percentages were calculated separately for each question using substantive responses to that question as the denominator.

5.2 Quantitative Learner Perceptions

Overall, learners evaluated the organisation, learning experience, assessment alignment, and synchronous components of the modules positively in both implementation settings (Table 1). Perceived achievement of the stated learning outcomes was rated positively by 87.1% of industrial responses and 90.6% of HE responses, with mean ratings of 4.35 (SD = 0.70) and 4.53 (SD = 0.85), respectively. Alignment between quiz questions and learning outcomes was also evaluated positively in both settings, with mean ratings of 4.55 (SD = 0.67) in industry and 4.75 (SD = 0.65) in HE. Synchronous online sessions were similarly perceived as supporting consolidation of prior asynchronous learning, with 87.1% and 88.3% positive responses in industry and HE, respectively.

Table 1: Selected learner-evaluation outcomes by implementation setting.

Questionnaire Indicator	Industry M (SD)	Industry % 4–5	HE M (SD)	HE %4–5
Content was well organised	4.52 (0.62)	93.3%	4.73 (0.64)	95.3%
Navigation through the module was smooth	4.35 (0.87)	82.3%	4.62 (0.67)	95.3%
Time allocated to the module was appropriate	3.79 (1.16)	66.1%	4.17 (1.14)	76.5%
Interest increased while progressing through the module	4.59 (0.56)	96.8%	4.69 (0.71)	94.1%
Quiz questions were aligned with the learning outcomes	4.55 (0.67)	93.6%	4.75 (0.65)	94.1%
Online sessions were dynamic and supported consolidation	4.44 (0.76)	87.1%	4.52 (0.81)	88.3%
Perceived acquisition of the learning outcomes	4.35 (0.70)	87.1%	4.53 (0.85)	90.6%

Note: Industry: n = 62; HE: n = 85. Items were rated on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree). The column *% 4–5* represents the proportion of positive responses (ratings 4–5).

Ratings concerning organisation and engagement were also high. The organisation of module content received mean ratings of 4.52 (SD = 0.62) in industry and 4.73 (SD = 0.64) in HE. Navigation was somewhat more variable in the industrial implementations (M = 4.35, SD = 0.87; 82.3% positive) than in HE (M = 4.62, SD = 0.67; 95.3% positive). Learners also reported increased interest as they progressed through the modules, with mean ratings of 4.59 (SD = 0.56) in industry and 4.69 (SD = 0.71) in HE; 96.8% and 94.1% of responses were positive, respectively.

In contrast, the adequacy of the time allocated to the modules was the least positively evaluated of the selected dimensions. The pooled rating was 3.79 (SD = 1.16) in industry, with 66.1% of responses selecting 4 or 5, compared with 4.17 (SD = 1.14) and 76.5% positive responses in HE. Module-level inspection indicated that lower ratings of time allocation were not confined to a single module, suggesting that this represented a broader implementation consideration rather than a module-specific issue.

5.3 Qualitative Learner Feedback

Open-ended responses were analysed separately for module organisation, learning resources, and teaching approach. Responses could be assigned to more than one category when multiple aspects were mentioned; therefore, percentages within each question are not mutually exclusive.

Table 2: Key findings from open-ended learner feedback on module organisation, learning resources, and teaching approach.

Question Area	Finding	Industry %	HE %	Total n (%)
Organisation – valued aspects	Clear structure and organisation	35.2	37.0	49 (36.3)
	Variety of learning resources/activities	38.9	34.6	49 (36.3)
Organisation – room for improvement	More time / lower workload	34.1	17.9	30 (23.4)
Resources – preferred	Quizzes	45.7	44.2	59 (44.7)
	Videos	39.1	47.7	59 (44.7)
Resources – least preferred	No disliked resource	34.2	34.6	40 (34.5)
	Videos	13.2	16.7	18 (15.5)
Teaching – valued	Instructor support and responsiveness	21.4	26.8	31 (25.0)
	Gamified/quiz-based interaction	19.0	25.6	29 (23.4)
	Clear explanations	16.7	17.1	21 (16.9)
Teaching – least valued	No disliked teaching aspect	52.8	50.0	59 (50.9)
	Synchronous-session schedule	8.3	15.0	15 (12.9)
	Time/workload pressure	19.4	5.0	11 (9.5)

Note: Percentages use question-specific substantive responses as denominators and are not mutually exclusive because multiple coding was permitted.

Regarding module organisation, the most frequently valued aspects were the variety of learning resources and activities and the clear structure of the modules, each identified in 49 of 135 substantive responses (36.3%). These patterns were similar across settings. The principal organisational concern was related to time and workload, mentioned in 30 of 128 responses (23.4%). This concern was proportionally more frequent in the industrial setting (34.1%) than in HE (17.9%), consistent with the lower quantitative ratings for adequacy of time allocation.

For learning resources, quizzes and videos were the most frequently preferred formats, each identified in 59 of 132 substantive responses (44.7%). Preference for quizzes was similar across the two settings, while videos were more frequently identified as a preferred resource in HE (47.7%) than in industry (39.1%). At the same time, 40 of 116 responses to the least-preferred-resource question (34.5%) explicitly indicated that no resource type was disliked. Among those identifying a specific least-preferred format, videos were mentioned most frequently (18; 15.5%). The appearance of videos among both the most- and least-preferred formats suggests variation in individual resource preferences and supports using complementary learning formats rather than relying on a single resource type.

Regarding the teaching approach, instructor support and responsiveness were the most frequently identified valued feature (25.0%), followed by gamified or quiz-based interaction during synchronous sessions (23.4%) and clear explanations (16.9%). When learners were asked what they liked least about the teaching approach, approximately half of the responses explicitly identified no disliked aspect (50.9%). Among specific concerns, the timing and scheduling of synchronous sessions was most frequently mentioned (12.9%), followed by general time constraints or workload pressure (9.5%).

Overall, the open-ended feedback contextualised the quantitative findings by identifying clear organisation, varied learning resources, instructor support, and interactive teaching as valued components of the learning experience. Synchronous sessions appeared to add value through interactive and gamified activities, although their timing and scheduling represented a practical challenge for some learners. General time and workload constraints also emerged as an implementation consideration, particularly in the industrial setting. Taken together, these findings support the potential transferability of the instructional design and pedagogical structure across industrial and HE contexts, while highlighting the importance of accommodating learners undertaking competency development alongside other responsibilities.

6. Conclusion

This paper presents a scalable, work-integrated e-learning model designed to support competency development across geographically distributed learners while accommodating different educational backgrounds and professional constraints. Implementation in both industrial and HE settings was associated with broadly positive learner perceptions, particularly regarding module organisation, learning resources, assessment alignment, instructor support, and interactive synchronous activities. The consistency of these perceptions across the two settings supports the model's potential applicability across different professional and educational contexts.

The findings also provide insight into specific features of the instructional design. High perceived achievement of learning outcomes, together with positive perceptions of instructor support and responsiveness, are consistent with previous research emphasising the importance of instructional support within flipped-learning environments (Thai et al., 2020; Gentile et al., 2022). Similarly, learners reported increasing interest as the modules progressed and frequently identified gamified and quiz-based synchronous activities as valued features. These findings are consistent with evidence that gamification can support learner motivation, engagement, and participation (Diaz and Estoque-Loñez, 2024; Su et al., 2025). Quizzes were also among the most frequently preferred learning resources, while quiz–learning outcome alignment was rated highly in both settings. The preference for quizzes is consistent with the rationale for incorporating retrieval practice and formative self-assessment into the learning pathway (Bertilsson et al., 2021). In parallel, the high perceived alignment between quiz questions and learning outcomes supports the model's constructively aligned assessment architecture. These associations should nevertheless be interpreted as learner perceptions and do not establish causal relationships between individual design elements and learning outcomes.

Importantly, time allocation was the least positively evaluated of the selected quantitative dimensions, while workload constraints and the timing of synchronous sessions also emerged from the open-ended feedback. This is particularly relevant to the model's objective of enabling learning alongside professional responsibilities. The modular architecture allows delivery to be compressed or extended according to organisational and learner needs; however, the findings suggest that flexibility should encompass not only asynchronous access to learning materials but also the overall pacing of the programme and the scheduling and spacing of synchronous activities.

The present evaluation is limited to self-reported learner perceptions and therefore does not establish objective competency acquisition, long-term learning transfer, or workplace impact. Moreover, the model is intended to complement rather than replace the laboratory and workplace-based training required for practical biomanufacturing competencies. Future research should therefore examine competency development and transfer using objective measures, evaluate longer-term workplace outcomes, and investigate how programme pacing and synchronous-session scheduling influence the experience of learners undertaking professional development alongside other responsibilities.

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Ethics Declaration

This article is based on a retrospective secondary analysis of educational data originally collected as part of the regular implementation and evaluation of an e-learning programme. At the time of data collection, the programme was not planned as a research study. Therefore, no separate consent for scientific secondary analysis and publication was obtained at that time.

The presented secondary analysis was reviewed prior to resubmission by the LUNEX Research Ethics Committee of LUNEX University of Applied Sciences and, by decision dated 27/08/2026 under file number 26_R_4910137, was approved.

AI Declaration

In developing the e-learning model, the instructors used artificial intelligence (AI) tools to support the development of QBs and English-language proofreading. The QBs were based on educational content originally created by the instructors, and all AI-assisted outputs were carefully reviewed, revised, and validated by the instructors before implementation.

In preparing this manuscript, ChatGPT (OpenAI) was used to support English-language editing and to assist with the descriptive qualitative content analysis, as detailed in the Methods. AI-assisted analytical outputs were reviewed against the original responses, ambiguous classifications were manually reviewed, and final coding decisions remained with the authors. The authors reviewed and edited all AI-assisted outputs and take full responsibility for the analysis, interpretation, and content of the manuscript.

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