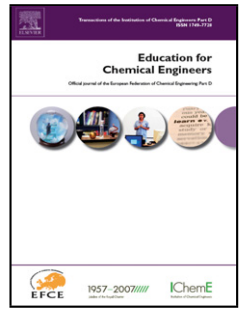

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Mobile learning in chemical engineering: An outlook based on case studies

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Graphical Abstract

Highlights

- M-learning methodology for teaching Chemical Engineering.
- The use of smartphones gains attention and involvement of students in classroom.
- Mobile devices as a useful tool for developing dynamic classes.
- Review of the implementation of M-learning in case studies of chemical engineering.
- A broad range of platforms is available for the development of M-learning.

Abstract

In the context of the electronic learning (E-learning) methodology, mobile learning (M-learning) focuses on the use of portable technology (such as mobiles or tablets) and the mobility of students. E-learning, and particularly M-learning, can be implemented in combination with other pedagogical methodologies for chemical engineering teaching and learning. We can consider that the vast majority of undergraduates own personal mobile devices nowadays. Moreover, many case studies have shown that M-learning is an effective methodology to capture students' attention and to actively engage them in the learning process. In most cases, lecturers have reported an improvement in both academic performance and qualifications and have expressed a favourable opinion towards this type of initiative in surveys. In line with the increasing interest in the incorporation of E-learning, this review discusses cases studies based on M-learning within the field of chemical engineering teaching through different technological platforms and apps which can be installed or directly used on mobile devices. All the platforms described in this work offer a free version, emphasizing the possibility of extending this methodology within the university with no need for additional economic resources.

Keywords: M-learning; Mobile devices; Chemical Engineering; Higher Education; Review.

1. Introduction

Active learning has been considered a valuable tool to motivate students and capture their attention in the classroom since the beginning of the '90s (Bonwell and Eison, 1991). In this context, the number of teaching experiences and case studies found in literature during this decade already suggests that active and cooperative learning methods facilitate both learning and the acquisition of interpersonal and thinking skills (Felder, 1995; DiBiasio and Groccia, 1995; Raju and Cooney, 1998). Besides, interest in the integration of active learning in different disciplines of chemical engineering has grown since the implementation of the Bologna Process and the European Higher Education Area. Under this context, over the last few years, the implementation of active learning has promoted a real change in the roles of students at universities, moving from mere spectators to active participants (Marjan and Mozhgan, 2012; Rezaev, 2010).

In this new perspective, the students themselves are part of the drive for the knowledge generation with more autonomy, considering their personal, professional, and social attributes. Thus, the entire university community has understood the need to actively engage students in the learning process as a key strategy to improve academic results. At the same time, the student community no longer accepts lectures based on conventional teaching methodologies that do not consider their leading role. As a consequence, numerous approaches have been developed since the beginning of the 21st century to turn the classroom into a highly dynamic environment (Ghafarpour and Moinzadeh, 2020). Among them, the most popular methodologies developed for undergraduate teaching are: adaptative tests (Rubia and Sacha, 2020), design thinking (Schwarzman and Buckley, 2019), flipped classroom (Rodríguez-Chueca et al. 2019; San-Valero et al. 2019), gamification (Rodríguez et al. 2018), learning-by-doing (Dominguez-Ramos et al. 2019; Negro et al. 2019), learning service (Rodríguez-Izquierdo, 2020; Bandi, 2020), problem-based learning (De Araújo et al. 2020; Ruiz-Ortega et al. 2019) and electronic learning (E-learning) (Krajnc, 2012). All these pedagogical methodologies encourage active participation as well as the involvement of the students in their lessons and the learning process.

Particularly, E-learning consists of an innovative methodology that supports individual and group work, providing students with flexibility in terms of time and space. This methodology enables a reduction of face-to-face contact and simultaneously it can be subjected to a series of standards or rules set by the administrators of the different platforms.

Besides, E-learning constitutes a powerful methodology based on the use of Information and Communication Technologies (ICTs) which have revolutionized the education field (Krajnc, 2012). The principle of E-learning lies in the utilization of electronic devices as a vehicle for teaching and learning. In turn, E-learning includes a series of methodologies such as Blended learning (B-learning), Ubiquitous learning (U-learning), and Mobile learning (M-learning). B-learning combines conventional and Internet-based learning, offering the main advantages of both systems (Cheah et al., 2016). U-learning consists of the use of computers and tools such as videoconference or augmented reality applied to any subjects in any place and at any time (Cárdenas-Robledo and Peña-Ayala, 2018). Finally, M-learning takes advantage of the possibilities offered by mobile devices, which enable students to learn without being in a fixed location. In fact, M-learning has drawn growing attention in recent years as it provides a dynamic learning environment supported by small and easily portable technological devices, including tablets or mobile phones, in most cases with Internet access (Crompton et al., 2018; Purwanti et al., 2019). Thus, the number of mobile users worldwide stood at 6.95 billion in 2020, with forecasts suggesting this is likely to rise to 7.1 billion in 2021. Besides, the number of mobile users worldwide is projected to reach 7.41 billion in 2024 (Statista, 2020). Taking into account this last option, the model Bring Your Own Device (BYOD) consists of the use of students'own devices instead of those provided by schools or faculties (Blaser, 2019).

Doubtless, the convenience of applying E-learning depends on the difficulty of the subject and students' level of knowledge in a specific topic. In this sense, the main advantage of E-learning, which can be combined with other methodologies, is the possibility of involving a large number of students, who have access to the Internet, on an electronic device (GSMA, 2020). On the other hand, M-learning is deemed as the most interesting ICT-based method at university level, as the vast majority of students have a personal mobile phone or a tablet (Poushter, 2016). Thus, mobile devices are becoming increasingly popular teaching tools at universities, as well as at high school and even at the primary level through the use of tablets. Figure 1 shows a scheme of the most frequently implemented methodologies that can be combined with E-learning and particularly, with M-learning.

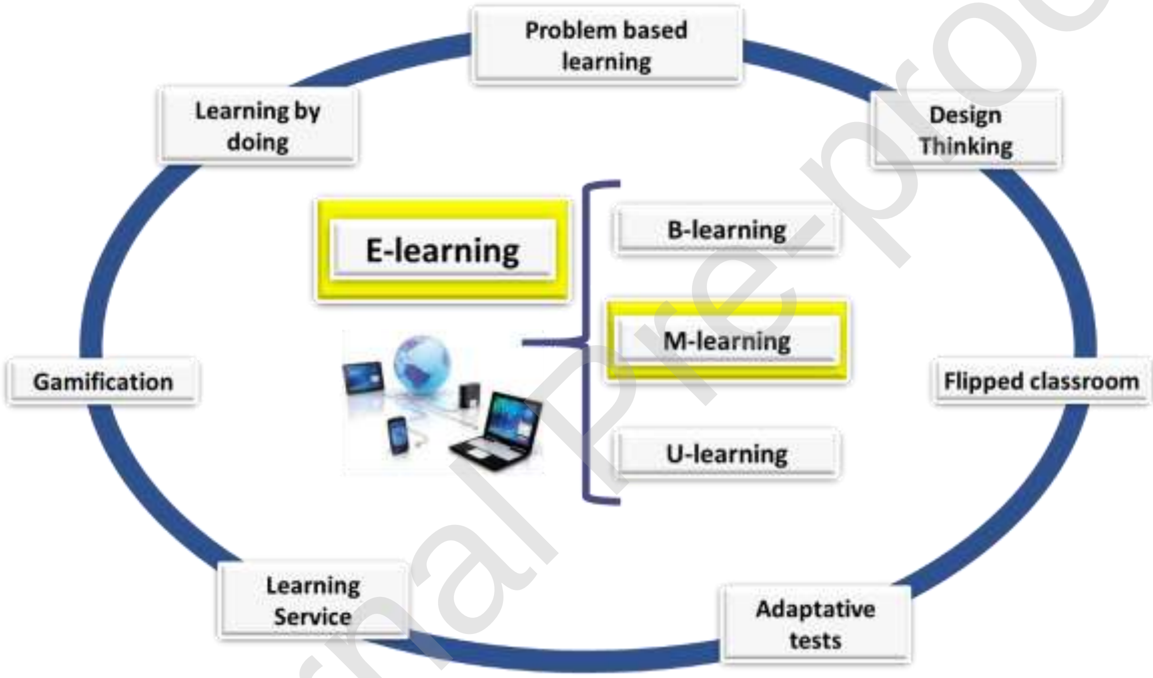

Figure 1. Methodologies that could be applied within E-learning.

The utilization of mobile devices is likely to be promoted in the education field in the coming years. Thus, many lecturers have already decided to incorporate them as useful resources for the development of lessons. This point is particularly relevant among undergraduates as the inclusion of mobile devices during lesson time has been shown to help maintain the concentration and attention of students. It has been claimed that the use of mobile phones should be discouraged due to the associated hyperconnectivity. However, these devices could also be employed as a way to attract and keep the attention of students, promoting high participation and proactivity (Rivero and Domínguez-Ramos, 2020).

Despite the existence of reviews on M-learning focusing on primary and higher education (Chee et al., 2017; Chen et al., 2019; Devers and Panke, 2018), there are very few studies dealing with the application of M-learning within the discipline of engineering, and specifically, in the field of chemical engineering. This work aims to review and discuss case studies related to the use of M-learning methodology. In this context, mobile phones or tablets could be a useful tool to capture students' attention as well as to promote class participation. We also cover the main features of the different applications used for the implementation of this methodology.

2. Main platforms used for M-learning

The growth in mobile device usage has progressively promoted the utilization of platforms or applications (apps) as learning tools. Simultaneously, it has fostered the deployment of new pedagogical methodologies like M-learning. This learning approach is based on the use of mobile devices such as mobile phones, tablets, iPads, PDAs, audio-players, e-readers, graphing calculators and iTouches, among others. Different platforms and apps used in M-learning of special interest within the specific field of chemical engineering teaching are introduced in this section, emphasizing their main features and functions. Specifically, this review focuses on the platforms which are effective to teach chemical engineering using M-learning methodology. These tools have been classified according to the main purpose of the application within the classroom: i) direct identification and assessment of the students' learning outcomes by performing tests (Kahoot, Socrative and Mentimeter), ii) comprehensive enhancement of students' learning process by building digital diagrams, charts, presentations or flashcards, among others (Mindomo, Genially, social networks and Quizlet), and iii) on-line sharing of the contents of different subjects (Padlet, Google Classroom, Moodle and Concept Warehouse), as illustrated in Figure 2. It is important to remark that these apps could be used for several of the approaches previously commented.

Figure 2. Applications used in different case studies of chemical engineering: (i) Kahoot, Socrative, and Mentimeter for the identification and assessment of students learning outcomes; (ii) Mindomo, Genially, Quizlet and social networks for the enhancement of student's learning process and (iii) Google Classroom, Moodle and Padlet for sharing on-line contents.

2.1 Platforms used for testing students

Although Kahoot, Socrative and Mentimeter present a wide range of functions, the main use of these apps for teaching purposes is to conduct tests in the classroom to assess the students' learning outcomes. Thus, these platforms are considered useful tools for lecturers.

2.1.1 Kahoot

Kahoot is deemed as one of the most well-known tools certified by Education Alliance Finland that enables the development of effective and entertaining classes (Education Alliance Finland, 2020). Kahoot is a dynamic application for the implementation of questionnaires that can be prepared in a short time. The questions are visible on a shared screen for the entire class and the students reply individually on their smartphones. It also includes the possibility of answering in anonymous mode. In this context, this app allows users to work with different options such as quizzes or multiple-choice, true or false, poll, slide, puzzle or open-ended questions, with the possibility of including images in the answers. The detailed characteristics of each question type are described on the official website (Kahoot, 2020). Besides, Kahoot enables students to follow up with online lessons via mobile devices when physical attendance is not possible.

Although the app offers a wide range of possible question types, only a selection is available with the free version of Kahoot. In this sense, the app presents three different kinds of subscriptions: Free, Pro and Premium versions. The accessibility to each question type is summarized in Table 1 according to the subscriptions mentioned. Thus, Pro and Premium versions include advanced features such as wider access in terms of question types, advanced reports, games and monitoring the tests performed by students.

Table 1. Queries offered by each kind of Kahoot's subscription.

Type of Questions	**Free**	**Pro**	**Premium**
Quiz	✓	✓	✓
True / False	✓	✓	✓
Images as answer	✓	✓	✓
Poll	✗	✓	✓

Slide	✗	✓	✓
Puzzle	✗	✓	✓
Open-ended question	✗	✓	✓

2.1.2 Socrative

Nowadays, Socrative has become one of the most popular classroom tools since this app does not require previous registration. On the one hand, from the teacher's perspective, the use of this platform results in significant time savings when it comes to preparing lessons and correcting questionnaires. The answers can be checked in real-time, obtaining instant feedback from students and showing the shortcomings of the classroom, as displayed in Figure 3.

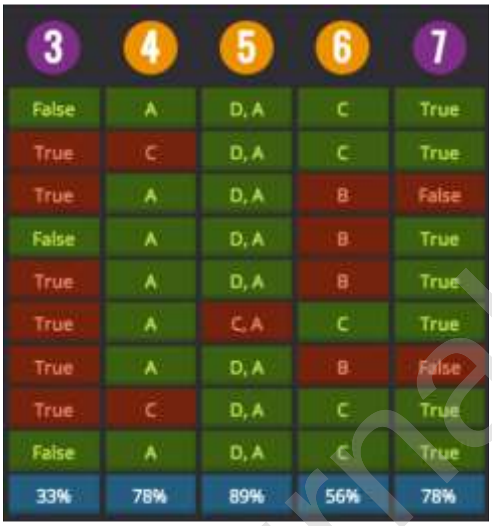

Figure 3. Example of a multiple-choice activity performed with Socrative.

On the other hand, from the student's perspective, this tool changes the traditional classroom environment, resulting in an active engagement in the proposed educational activities. Moreover, different settings are available depending on the type of user in the following categories: students, kindergarten to grade 12 (K-12), higher education and corporations, as reviewed in Table S1 of the Supplementary Information (Socrative, 2020).

In addition, all users can take advantage of the main features provided by Socrative: quizzes, quick sections (multiple-choice, true or false and short answer), or different personalized activities. However, the free version limits the available functionalities in accordance with the settings displayed in Table S1. Although students have free access to the entire platform, K-12, higher education and corporation subscribers (teachers, lecturers and enterprises, respectively) have to pay a certain fee, with different characteristics such as the number of students per room or number of public and private rooms. Moreover, Socrative can be used on different devices, including smartphones, tablets, laptops, computers and Chromebooks. In this sense, the appearance and functions of the app are adapted to the type of user. Hence, Socrative can be easily implemented in classrooms.

2.1.3 Mentimeter

Mentimeter enables the preparation of both appealing and interactive presentations for different types of audiences (Mentimeter, 2020). This platform allows students to answer open-ended questions embedded in presentations or videos using their smartphones or tablets. Thus, Mentimeter is considered an entertaining, engaging and highly interactive mobile learning tool. Mentimeter for teachers and students has three different monthly fees: Free, Educational Basic and Educational Pro. The main differences between these subscription modes are the number of questions and quizzes available per presentation and other specific advanced settings.

2.2 Platforms used for improving the quality of classroom learning

The platforms collected in this sub-section, Mindomo, Genially, Social networks and Quizlet, are mainly aimed at improving the quality of the learning process in the classroom by creating diagrams, charts, presentations or flashcards, among others.

2.2.1 Mindomo

Mindomo is a tool for building digital concept maps, diagrams, Gantt charts, and particularly mind maps. This kind of diagram displays single words or phrases hierarchically connected by arrows and lines (Jbeili, 2013).

Although the available applications in this platform are the same regardless of the kind of user (education or business), different types of subscriptions are offered in line with other cases: Free, Basic, Teacher, Classroom & Teacher and Free, Premium, Professional and Team for education and business, respectively (Mindomo, 2020). The main characteristics for education and business users, including the monthly charge, are summarized in Tables S2 and S3 of the Supplementary Information, respectively. Finally, Mindomo is available in widespread operating systems such as Windows, Linux, iOS and Android, among others.

2.2.2 Genially

Genially is versatile online software designed for the preparation of interactive content in the form of presentations, dossiers, infographics, interactive images, quizzes, maps or lists. The contents can be shared with different audience types via email, social networks, blogs and Moodle, among others. In this way, different plans are offered by Genially to the users: Free, Pro, Master and Team subscriptions (Genially, 2020).

2.2.3 Social networks

Facebook, Instagram, WhatsApp, Snapchat or Twitter are popular social networking sites. Their popularity can be exploited for teaching purposes and, therefore, the interest of lecturers in social network functions for teaching has increased over the last few years. Social networks can greatly increase motivation, participation and collaboration among students since many of them have access to these free social networks. In this way, both lecturers and students can exploit the full potential of the features offered by social networks. Thus, Instagram, Snapchat, or YouTube can be used for sharing media, networks, photos, and videos; Twitter for finding and using common tags; and Facebook or WhatsApp for encouraging communication between students and their lecturers. Nevertheless, social networks can pose some disadvantages, such as a lack of control for inappropriate content or the possibility of distraction for students (Aydin, 2012; Lim et al., 2017).

2.2.4 Quizlet

With this platform, users can create flashcards to memorize and revise the lessons learned in class in an engaging way on their mobile devices. Moreover, this tool allows the combination of text with images, audios and videos through games and activities. Quizlet also promotes social interaction among users with the tool Quizlet Live. Gaming activities allow students to work in teams and playfully compete against each other, sharing the acquired knowledge contents in the classroom. Three types of subscriptions are available for Quizlet: Free or basic, Quizlet Plus for learners and Quizlet for teachers. One negative aspect is that the free version is supported by advertisements, which can distract students. This issue is avoided with the Quizlet Plus for learners and the Quizlet teacher versions. Furthermore, under these subscription modes, the users have access to the content previously created by others (Quizlet, 2020).

2.3 Platforms used for sharing contents

In addition to the functionalities mentioned in previous sections 2.1 and 2.2, some platforms, such as Padlet, Google Classroom, Moodle and Concept Warehouse can be used for improving the accessibility of digital information sharing online content.

2.3.1 Padlet

Digital tools offer the possibility of working with an electronic and virtual board using iOS, Android and Kindle devices, among others (Padlet, 2020). In this sense, Padlet is an online blank wallboard that can be used by invited participants to collaborate, for example, in collecting ideas and sharing information. Padlet provides a user-friendly interface for audiences of all ages. The main advantages of this platform are: (i) the high number of available languages (up to 29); (ii) the compatibility with different file formats, including pictures or videos from a phone, links from the web, files from Photoshop, AutoCAD, YouTube, social media, among others; and (iii) the possibility of exporting information as PDF, CSV, Image or Excel File. The platform can be used for both education and business purposes. Furthermore, there is a Padlet free version with basic functionalities, but school or business subscription brings advanced features to the users with greater potential.

2.3.2 Google Classroom

Google Classroom belongs to Google Apps for Education, which promotes E-learning and can be especially used for M-Learning methodologies. This free tool enriches the learning experience in the traditional classroom through numerous activities and possibilities. The platform has been designed considering both the needs of lecturers and students. On the one hand, lecturers can create online lessons, share educational material with their students and organize online classes and set a variety of assignments. In addition, they can monitor the progress of their students. On the other hand, students can easily access the teaching contents and tasks previously prepared by lecturers and use the platform to communicate with both lecturers and other students (Google Classroom, 2020). Google Classroom can be supported by Windows, Android, iPhone or iPad, Mac, Web-based and Windows Mobile.

2.3.3 Moodle

Moodle is one of the most common and well-known online learning management systems (Moodle, 2020). It enables lecturers to create personalized virtual spaces with dynamic courses for students to learn whenever and wherever. In this sense, Moodle has been designed as a free, accessible and intuitive platform to work on all kinds of devices.

Moreover, Moodle offers the performance of up to 20 different kinds of activities: forums, glossaries, assignments, quizzes, choices, database activities and multiple-choice tests with simultaneous correction, among others. Both lecturers and students can receive automatic notifications on new assignments, task deadlines and forum posts. Forum posts facilitate communication between lecturers and students and their counterparts. Similarly, as in the case of the Google Classroom platform, lecturers and students can track the process and completion of the different tasks within the frame of a lesson.

2.3.4 Concept Warehouse

The Concept Warehouse platform is like Moodle (Concept Warehouse, 2020). This platform, created by the American Institute of Chemical Engineers (AIChE) and mainly implemented across America, allows users to: (i) share experiences and contributions with society, (ii) find and create, conceptual questions with multiple search options, (iii) collect students' answers in a variety of ways, and (iv) visualize results for class use and educational research. In this context, the design of questions with multiple search options could be shared with the educational community throughout the world. Besides, it is also possible to download predefined concept inventories, charts, diagrams, and other materials related to the chemical engineering field, within specific areas such as Materials Science, Fluid Dynamics, Thermodynamics, Thermal Transport, and General Chemistry.

3. M-learning case studies applied to chemical engineering

This section presents a review of different case studies based on M-learning as a pedagogical tool within the chemical engineering teaching field. The following case studies are included according to: i) the platform and app used, previously discussed in section 2; and ii) the content reviewed, as summarized in Tables 2 and 3, respectively.

3.1 Case studies based on Kahoot

As mentioned in section 2.1.1, Kahoot allows users to create questionnaires, which are visible on a shared screen. In this sense, Kahoot has been applied in a wide range of case studies in the chemical engineering field due to the many functions and types of questions available on this platform. Firstly, Cutri et al. (2016) applied Kahoot in Chemistry courses for both freshman and sophomore students in a Chemical Engineering School, with the main purpose being to reinforce knowledge acquired in previous lessons. The total number of quizzes was 21, with a duration from 10 to 15 minutes and with 5-6 questions per quiz. Despite having some problems related to Internet access, some benefits were obtained by using Kahoot as an M-learning methodology, including immediate feedback, a high level of student interaction and involvement, the possibility to adjust methodologies for learning improvement and learning in a fun and enjoyable environment.

Furthermore, Grinias (2017) created a repository of review questions for Analytic Chemistry exams. Nevertheless, some limitations were experienced when preparing exams such as character number restrictions or a fixed maximum time for each question (95 characters and 120 seconds, respectively). On the other hand, Urban et al. (2017) employed Kahoot as a voluntary quiz based on video content for Chemistry for Life Sciences. The use of Kahoot provided students with a stimulating experience as well as increased motivation. Ares et al. (2018) improved students' academic performance in the final exam by using Kahoot as a pedagogical tool in a Chemistry course, increasing the average score and the percentage of students that passed the final exam (almost 50 %). In this case, Kahoot facilitated the study process and, at the same time, contributed to improved memory capacity. The same results were observed by Parra-Santos et al. (2018), showing that students' attention, motivation and enjoyment increased when a Kahoot survey was used in comparison to a conventional quiz.

Moreover, some authors have recently published studies in which Kahoot is used as a tool in chemical engineering lessons, including Santos-Dueñas et al. (2020), Matos et al. (2020), Álvarez-Torrellas et al. (2020) and Mosteo et al. (2020). Santos-Dueñas et al. (2020) highlighted the importance of using Kahoot for lecturers and students. On the one hand, they concluded that lecturers were motivated by the implementation of the tool due to the students' enthusiasm, and on the other hand, the students reinforced the contents acquired in previous lessons. The increase in student motivation is also highlighted by Álvarez-Torrellas et al. (2020), Matos et al. (2020) and Mosteo et al. (2020) who reported an improvement in the academic performance of the students and an increase in their motivation in the subjects of Kinetics and Chemical Reactors and Environmental Engineering in two Engineering Degrees. In this context, Mosteo et al. (2020) combined the use of M-learning with the implementation of a project-based learning methodology.

Apart from the use of Kahoot in classes, this methodology has been shown to be a useful tool at some recent and relevant conferences such as the 10th World Congress (WCCE10) (10^{th} World Congress of Chemical Engineering, 2017) and the Student Conference at the 3rd International Congress (SC-ICCE3) (ANQUE-ICCE 3 Student Conference, 2019) of Chemical Engineering respectively.

3.2 Case studies based on Socrative

This platform has been applied as one of the most common tools in M-learning teaching due to the large number of advantages highlighted in section 2.1.2. Frías et al. (2016) used Socrative with undergraduate students to teach chemistry. Socrative enables a follow-up of the progress made by students in real-time through mobile devices. The authors also reported a high level of student engagement due to the anonymous nature of all responses as well as the intuitive interface provided by the platform. Besides, Santos et al. (2016) focused on the creation of questionnaires based on chemical formulation and nomenclature by using this tool. In both cases, the final marks and rate of lesson attendance improved as well as the motivation of the students. In this sense, most of the students (71%) considered the use of Socrative as a great experience while over 19% considered it as an enriching experience (Frías et al., 2016). Furthermore, Cheah et al. (2016) developed multiple-choice and true or false quizzes in real-time as an effective learning tool for a Plant Safety and Loss Prevention course as part of a Chemical Engineering degree at the University of Singapore.

Additionally, Aranzabal et al. (2018) described the successful implementation of the Socrative feature ‘Space Race’ in a Process and Product Engineering course at the University of the Basque Country in Spain. This mode allows lecturers to monitor the continuous progress of students in real-time while they answer the questions. Likewise, Santos et al. (2019) enhanced chemistry laboratory classes through this platform. The authors created quizzes for students before and after the laboratory classes, increasing their academic performance and improving the relationship between lecturers and students. Also, Santos et al. (2019) measured student satisfaction of the use of Socrative, which was considered an easy and effective application; simultaneously, the authors suggest that Socrative can be used for assessment purposes. In this way, Socrative was also employed as a tool to set up surveys as discussed by San-Valero et al. (2019) and Ramirez et al. (2020).

Borreguero et al. (2020) promoted the use of Socrative as a tool to develop the Just In Time Teaching methodology in the frame of laboratory classes. This methodology aims at improving both theoretical and practical concepts as well as the laboratory safety rules. Finally, Romero et al. (2020), and Rivero and Domínguez-Ramos (2020) implemented quizzes in the frame of Industrial Chemical Processes and Life Cycle Assessment subjects.

3.3 Case studies based on Mentimeter

As mentioned in section 2.1.3, Mentimeter allows the creation of quizzes for students, and the results can also be checked by the lecturer in real-time. In this context, Rivero and

Domínguez-Ramos (2020) implemented Mentimeter in the subject Project Management of the Chemical Engineering degree at the University of Cantabria in Spain. The authors suggested that the use of mobile devices could greatly encourage the participation and involvement of students. They highlighted the benefits of following the responses marked by the students to adapt the contents and level of difficulty according to the results if necessary.

On the other hand, Rodríguez et al. (2018) underlined Mentimeter as an innovative tool in the chemical engineering degree, specifically for Process Control courses. The use of this platform brought about a real change in the teaching perspective due to its numerous possibilities. Moreover, traditional presentations were turned into slides with blank spaces to promote the active participation of students. Lecturers asked students about the blank spaces, thus improving the interaction between both groups and, at the same time, avoiding a methodology based on an entirely monotonous speech given by the lecturer. The questions were asked using the Mentimeter tool, and the students' answers were checked in real-time. Through this platform, the academic performance of students, both in terms of average score and exam pass rates, improved, with an increase of up to 91 percentage points in the latter.

3.4 Case studies based on Mindomo

As an example of the possibilities offered by Mindomo, a mind map on project management to be used in chemical engineering courses is shown in Figure 4. A mind map can be an effective tool for both teaching and self-study. At the end of a lesson, students can organize and interconnect the ideas and concepts learned in a mind map.

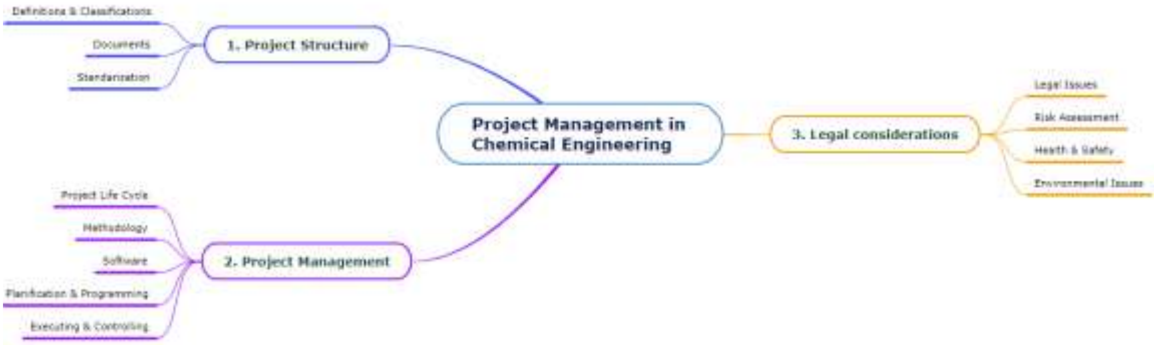

Figure 4. Illustrations of a mind map.

Moreover, Krzywicka and Grudziński (2019) made classes more attractive and motivated the students by having them use their mobile devices to build mind maps in the subject of Materials Science. All mind maps were then shared with the other students and lecturers responsible for the subject. Finally, students were surveyed to gather their feedback about the implementation of the use of multimedia, the Internet and ICT tools. The results showed a very good and general acceptance of the use of M-learning as an innovative educational technique.

3.5 Case study based on Genially

Santos et al. (2020) played a breakout game in a typical chemical engineering case study based on wastewater treatment. The activity was aimed at studying the effectiveness of chemical compounds to remove waste pollutants. The authors provided the clues for the breakout game in an interactive image made with the Genially platform, which included numerous queries. The students had to select the answer on their mobile devices under the proposed contents of Physics and Chemistry. The activity showed an increase in motivation and in the number of competences acquired by the students, such as teamwork, creativity and student-centred learning.

3.6 Case studies based on social networks

As discussed in section 2.2.3, social networks have been considered an innovative teaching tool due to their popularity among students. In this sense, Korich (2016) employed Instagram as a platform to reinforce concepts using mobile devices. The author posted problems and their solutions on Organic Chemistry, reaching out to students outside of the classroom. For its part, Lim et al. (2017) also proposed the use of Instagram and Snapchat for a chemistry laboratory course, encouraging other lecturers to implement social networks as a laboratory pedagogical tool due to the positive opinion of those involved. Hurst (2018) utilized Snapchat to teach chemistry, biochemistry and natural sciences. Both images and videos were shared to show the set-ups in the laboratory, providing an insight into research environments and academic life in the field of chemistry. Although the full social networking capabilities of Snapchat were not explored, student interest in the subject significantly increased. In addition, Burks et al. (2018) described how motivation in a chemistry course could be improved by using Twitter.

3.7 Case studies based on Quizlet

Krause et al. (2013) and (2014) implemented Quizlet in lessons as an M-learning methodology to improve conceptual understanding of contents previously studied in class. Initially, Krause et al. (2013) focused on quizzes based on Eutectic Phase Diagram Calculations and Microstructures. Subsequently, Krause et al. (2014) used Quizlet as a tool to teach Materials Science. Both studies reported the potential of Quizlet as a platform to increase the effectiveness of E-learning, highlighting teamwork as the main competence acquired by the students.

3.8 Case study based on Padlet

Despite the numerous benefits provided by the Padlet platform, there have been few reports of this platform being used for chemical engineering teaching because of the predominant presence of other platforms such as Kahoot and Socrative, which are considered more interactive. Nevertheless, the utility of Padlet was assessed in a chemical engineering degree as a pedagogical tool by Pardo-Cueva et al. (2019). The results showed that Padlet is an efficient and useful platform, regardless of the final mark obtained by the students in comparison with previous years. In addition, this work highlights the importance of ICTs in acquiring competences.

3.9 Case studies based on Google Classroom

Both Silverstein (2008) and Palmer (2016) have demonstrated the usefulness of Google Classroom as an M-learning platform. Firstly, Silverstein (2008) solved chemical engineering problems using an online spreadsheet on Google Docs. The problems were solved in teams by the students. When one of the group members edited the spreadsheet, this change simultaneously appeared on their screens. After the experience, a spreadsheet assessment was performed to analyze the viability of the platform. Results showed that the use of the Google-based spreadsheet effectively improves communication among participants and promotes teamwork competence. Palmer (2016) implemented Google sheets in a chemical engineering class to collect answers in real-time. The users of this platform can change their answers until the end of the exam with the possibility of interacting with other students. This methodology tries to avoid answers based on a random basis in the event of a lack of sufficient knowledge, as can occur with conventional multiple-choice quizzes. In addition, the lecturers can see the responses and the scores in real time, gathering information about the main shortcomings of students.

3.10 Case studies based on Moodle

Moodle has been implemented as a teaching tool in many universities. Nevertheless, more work needs to be done on using this app with mobile devices. In this context, Hsiung (2018) and Romero et al. (2020) have recently reported case studies in which Moodle is employed as an M-learning tool. Firstly, Hsiung (2018) applied this platform as an alternative to traditional teaching in chemistry courses. Within Moodle, students were given different questionnaires, which were always made available. The students considered the initiative to be a very interesting approach since the subject became more interactive and engaging, enhancing their knowledge in chemistry. Besides, Romero et al. (2020) provided students with quizzes, employing Moodle in the subject of Industrial Chemical Processes of the Industrial Technologies Engineering Degree at the University of Zaragoza in Spain. The authors highlighted the preference of students for the use of this platform versus Socrative, due to the fact that questionnaires are available throughout the entire course. Despite there being an increase in the final marks of the subject in comparison to previous academic courses, the authors suggested a combination of these platforms. Thus, Socrative can enhance lessons, while the use of Moodle promotes continuous study throughout the course.

3.11 Case studies based on Concept Warehouse

Concept Warehouse assists faculties within the discipline of chemical engineering with questions on material and energy balances, thermodynamics, transport phenomena, kinetics, reactor design and materials science. White et al. (2015) proposed concept questions to promote and evaluate student learning in real-time. As depicted in Figure 5, the students can answer and write an explanation for the questions on their mobile devices. Moreover, the lecturer can adjust the scheduled time of each question according to the performance of students. Students were given surveys to find out their perception of the activity and to improve the design of the tool.

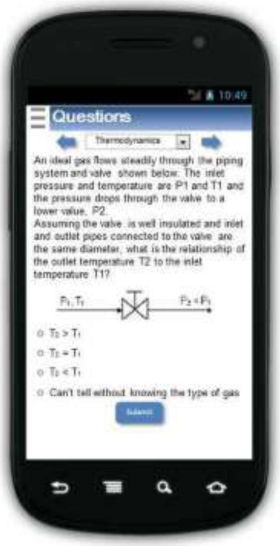

Figure 5. An illustration of one question proposed on the Concept Warehouse platform. Reprinted from White et al. (2015).

Table 2 provides an overview of the case studies based on M-learning that have been discussed in Section 3. They are displayed according to the platform and app type, including its official website. Table 3 shows the courses in which these apps have been used.

Table 2. Overview of the different case studies of section 3 in the chemical engineering field based on the M-learning methodology and classified according to the platform and app used, including its official website.

Section	Platform	References
3.1	Kahoot https://kahoot.com/	Cutri et al., 2016; Grinias, 2017; Urban et al. 2017; Ares et al. 2018; Parra-Santos et al. 2018; Santos-Dueñas et al. 2020; Matos et al. 2020; Álvarez-Torrellas et al. 2020; Mosteo et al, 2020.
3.2	Socrative https://socrative.com/	Frías et al. 2016; Santos et al. 2016; Cheah et al. 2016; Aranzabal et al. 2018; Santos et al. 2019; San-Valero et al. 2019; Ramírez et al. 2020; Borreguero et al. 2020; Romero et al. 2020; Rivero and Domínguez, 2020.
3.3	Mentimeter https://www.mentimeter.com/	Rodríguez et al. 2018; Rivero and Domínguez, 2020.
3.4	Mindomo https://www.mindomo.com/	Krzywicka and Grudziński, 2019.
3.5	Genially https://www.genial.ly/en	Santos et al. 2020.
3.6	Social networks https://www.youtube.com/ https://www.instagram.com/ https://www.snapchat.com/l/es/ https://twitter.com/explore	Korich, 2016; Lim et al. 2017; Hurst, 2018; Burks et al. 2018.
3.7	Quizlet https://quizlet.com/es	Krause et al. 2013; Krause et al. 2014.
3.8	Padlet https://padlet.com/	Pardo-Cueva et al. 2019.
3.9	Google Classroom https://classroom.google.com/h	Silverstein, 2008; Palmer, 2016.
3.10	Moodle https://moodle.org/?lang=en	Hsiung, 2018; Romero et al. 2020.
3.11	Concept Warehouse http://jimi.cbee.oregonstate.edu/concept_warehouse/	White et al. 2015.

Table 3. Overview of different case studies of section 3 in the chemical engineering field based on the M-learning methodology and classified according to the contents developed.

Contents	**References**
Basic operations in CE	Ramírez et al. 2020
Chemistry	Cutri et al. (2016); Grinias, 2017; Urban et al. 2017; Ares et al. 2018; Frías et al. 2016; Santos et al. 2020; Hsiung, 2018; Hurst, 2018; Burks et al. 2018.
Environmental Engineering	Mosteo et al, 2020
Fluid Mechanics	Parra-Santos et al. 2018
Industrial Chemical Processes	Romero et al. 2020
Inorganic chemistry	Santos et al. 2016
Kinetic and Chemical Reactors	Matos et al. 2020;White et al. 2015
Laboratory	Santos et al. 2019; Borreguero et al. 2020; Lim et al. 2017
Life Cycle Assessment	Rivero and Domínguez, 2020
Material and Energy Balances	White et al. 2015
Materials science	Krzywicka and Grudziński, 2019; White et al. 2015; Krause et al. 2014
Organic chemistry	Santos et al. 2016; Korich, 2016
Plant Safety and Loss Prevention	Cheah et al. 2016
Process and Product Engineering	Aranzabal et al. 2018
Process Control	Rodríguez et al. 2018
Project management	Rivero and Domínguez, 2020
Thermodynamics	White et al. 2015
Transport Phenomena	White et al. 2015

4. Other platforms employed in M-learning

Apart from the platforms and apps discussed in the previous sections, other studies have focused on the implementation of mobile devices in class using their own developed apps or other common platforms. This section presents a review of the different case studies within the chemical engineering field from 2009 to 2020, which is summarized according to app type or subjects in Tables 4 and 5 respectively.

Table 4. Overview of other case studies in the chemical engineering field, based on the M-learning methodology and classified according to the type of platform employed.

Type of platform	**References**
Based on videos	Benedict and Pence (2012); Ardisara and Fung (2018); Pölloth et al. (2020)
Cell-phone flash cards	Pursell (2009)
General apps	Libman and Huang (2013); McCollum et al. (2014); Wijtmans et al. (2014); Li et al. (2014); Casas and Estop (2015); Guerrero et al. (2016); Van Dyke and Smith-Carpenter (2017); Chow et al. (2018); Rathod et al. (2019); Sousa-Lima et al. (2019); Paniagua et al. (2019); Fatemah et al. (2020)
Mobile games	Winter et al. (2016); Kiat Koh and Fung (2018); Jones et al. (2018); da Silva Júnior et al. (2020)
Quick response code (QR)	Bonifácio (2012); Bonifácio (2013)

Table 5. Overview of other case studies in the chemical engineering field based on the M-learning methodology and classified according to the contents developed.

Contents	**References**
Analytical chemistry	Libman and Huang (2013); Li et al. (2014)
Basic operations in CE	Paniagua et al. (2019)
Biochemistry	Libman and Huang (2013)
Chemistry	Bonifácio (2012); Bonifácio (2013); McCollum et al. (2014); Wijtmans et al. (2014)
Inorganic chemistry	Libman and Huang (2013); Sousa-Lima et al. (2019)
Laboratory	Benedict and Pence (2012); Guerrero et al. (2016); Van Dyke and Smith-Carpenter (2017); Kiat Koh and Fung (2018); Ardisara and Fung (2018); Chow et al. (2018); Rathod et al. (2019); Pölloth et al. (2020)
Material science	Casas and Estop (2015)
Organic chemistry	Pursell (2009); Libman and Huang (2013); Winter et al. (2016); Jones et al. (2018); Sousa-Lima et al. (2019); da Silva Júnior et al. (2020); Fatemah et al. (2020)
Physical chemistry	Libman and Huang (2013)

In this context, Pursell (2009) implemented M-learning methodology with cell phone flash cards to teach organic chemistry by introducing an alternative organic chemistry pedagogical approach to conventional methodologies, simultaneously increasing the participation of undergraduates. Additionally, Bonifácio (2012) presented a quick response code (QR) as an M-learning tool to teach chemistry, specifically the periodic table, as illustrated in Figure 6. This author also provided students with QR code access to important information on Nobel Prizes in Chemistry (Bonifácio, 2013).

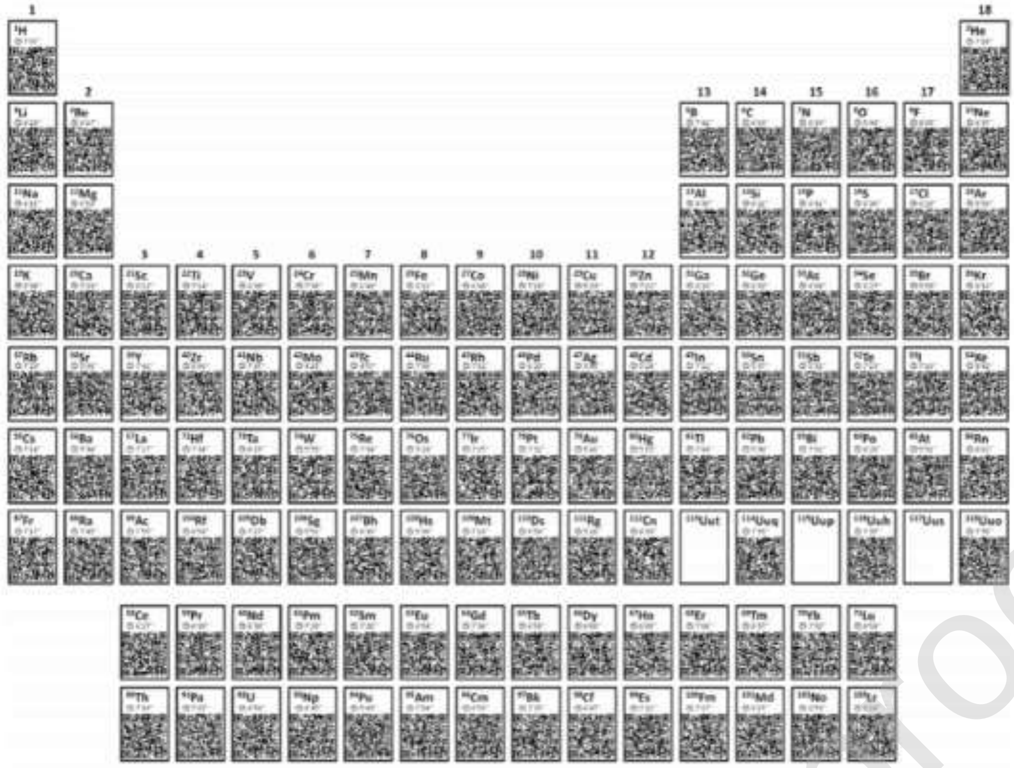

Figure 6. An illustration of the QR audio periodic table. Reprinted with permission from Bonifácio (2012). Copyright (2012) American Chemical Society

Moreover, general and analytical chemistry was taught to undergraduates by sharing video contents on laboratory instruments and procedures (spectrophotometer, gas chromatography with flame ionization detector, X-ray fluorescence spectrometer, direct mercury analyzer and titrations) (Benedict and Pence, 2012). The videos could be seen by using mobile devices to read barcodes, as illustrated in Figure 7. The results of the project showed that this approach was successful as an M-learning tool. Therefore, as reported by Libman and Huang (2013), a larger number of apps to teach inorganic, organic, analytical, physical chemistry and biochemistry are available on both Android and iOS operating systems.

Figure 7. An illustration of the spectrophotometer video and its barcode. Reprinted with permission from Benedict and Pence (2012). Copyright (2012) American Chemical Society.

McCollum et al. (2014) and Wijtmans et al. (2014) employed mobile devices, such as iPad, to show 3D molecular structures and to promote both representational and visuospatial competences. They also observed an important increase in the ability to correctly interpret 3D chemical structures in comparison to previous academic years, highlighting the prominent role that mobile devices could have for undergraduate education in the future. In this way, Li et al. (2014) also underscore the utility of the iPad for nuclear magnetic resonance spectroscopy data processing with significant time savings during Analytic Chemistry classes and exams.

Casas and Estop (2015) presented a free app as an example of 3D application design to teach crystallography concepts, which require high capacity for abstraction and spatial vision. The authors encouraged the use of these tools in class and the development of task-specific ones for teaching purposes. Moreover, organic chemistry was taught by using a mobile game called “Chairs!” for one-hour lessons (Winter et al., 2016). Particularly, this game focused on the ring flip of cyclohexane and it had a positive effect on students. Besides, other concepts, such as mechanisms, resonance and structural symmetry were explained with this platform. In turn, Guerrero et al. (2016) promoted learning based on mobile devices for chemistry in the laboratory, showing the experimental steps to be followed interactively. The results obtained after the implementation of the M-learning strategies led to a reduction in the average time of the laboratory practice while improving the students' academic performance.

In this regard, Van Dyke and Smith-Carpenter (2017) developed a digital laboratory notebook in the frame of the BYOD philosophy. This notebook could be used as a secure data management system. As an interesting feature, it includes freehand drawing. The final remarks of this study highlighted the significant participation and collaboration of the students. In addition, this platform can be adapted to general undergraduate teaching as well as laboratory practice.

Mobile games have been suggested to serve as an effective teaching vehicle in both laboratory and organic chemistry. Firstly, the "ChemCharades" game can be used to teach students contents about laboratory instruments, glassware, different apparatus and techniques (Kiat Koh and Fung, 2018). Students are divided into groups and the game consists of one student attempting to deduce the answer to a concept based on the description given by other members of the same group. Hence, participation is promoted among students in the absence of the lecturer, increasing mutual collaboration. For its part, "Chirality-2" was created to teach organic chemistry (Jones et al., 2018). This mobile game allows users: i) to obtain medals according to the results obtained, ii) to track continuous progress, iii) to post scores, and iv) to compete with colleagues. Both games are available on iOS and Android operating systems, and show great potential for undergraduate teaching.

Mobile devices also enable users to record panoramic view videos. In this context, several laboratory techniques have been recorded in an organic chemistry course as reported by Ardisara and Fung (2018). Moreover, these devices could be used as a quantitative colour analysis tool in the laboratory for the determination of the concentration of unknown samples in terms of $KMnO_4$, $CoSO_4$, $NiSO_4$ and $CuSO_4$ (Chow et al., 2018; Šafranko et al., 2018). Rathod et al. (2019) also proposed the use of mobile devices for analyzing the colour of titration based on the phenolphthalein indicator.

Chemical nomenclature was also introduced by using a free mobile game that includes more than 700 questions as illustrated in Figure 8. Students revealed that the app was helpful as a pedagogical tool versus traditional teaching (Sousa-Lima et al., 2019). Also, a specific app was designed by Paniagua et al. (2019), in which mobile devices were employed to solve chemical engineering problems without data in the Basic Operations course. This initiative reduced stress in students and simultaneously increased their academic performance.

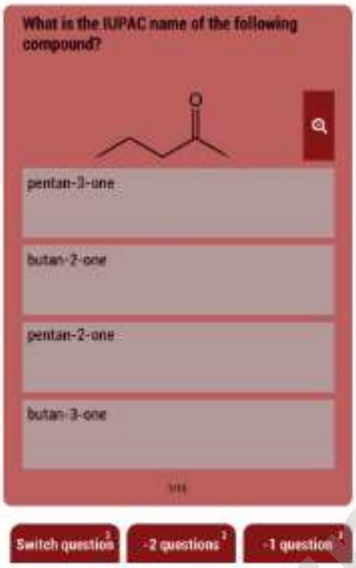

Figure 8. An illustration of one of the chemical nomenclature problems. Reprinted with permission from Sousa-Lima et al. (2019). Copyright (2019) American Chemical Society.

Finally, the so-called 'In Time Bomb Game' was created by da Silva Júnior et al. (2020). This mobile game involves students attempting to deactivate a time bomb while they answer random questions about the structure of organic compounds. Both lecturers and students revealed that the platform was an interesting tool to provide students with the required theoretical knowledge. In this way, laboratory classes were undertaken by undergraduates recording different types of videos: i) “tutorials”, ii) “do nots” and iii) “step-by-step” (Pölloth et al., 2020). “Tutorials” show and explain all relevant practical details for certain experimental procedures; “do nots” illustrate typical mistakes in the laboratory and “step-by-step” videos show the synthesis of compounds in the laboratory. For its part, Fatemah et al. (2020) promoted the visualization of 3D chemical structures to enhance both spatial and conceptual skills.

All the experiences previously mentioned, regardless of the platform used, were successful for teaching in higher education, showing the possibilities given by different innovative and technological tools to learn whenever and wherever possible. Nevertheless, the extensive implementation of M-learning tools as well as the comprehensive assessment of all their potentialities and limitations and their impact on students still require further studies. A SWOT analysis for M-learning methodology is presented in Figure 9 including the main Strengths, Weaknesses, Opportunities, and Threats of the M-learning tool. The effects of M-learning methodology in teaching and particularly, in university degrees, will be mainly influenced by the skills and capabilities of lecturers with apps, as well as the costs associated with their use. In this sense, the positive attitudes of lecturers will encourage the involvement of students in this kind of initiative. On the other hand, this methodology is subject to possible constraints on access to the Internet at universities. In addition, distraction, misuse, and lack of skills among students are the most common drawbacks reported (Al-Hamad et al, 2020) due to the use of mobile and portable devices being used for non-educational purposes.

Figure 9. SWOT for M-learning methodology.

5. Conclusions and future prospects

This work discusses the implementation of M-learning as a pedagogical methodology in higher education with a special emphasis on chemical engineering studies. The significant increase in the number of portable devices among students offers great opportunities to develop new learning methodologies. Specifically, more than 50 references were assessed, with most of the case studies covered in the field of chemical engineering.

The most common platforms and apps used for teaching purposes were analyzed describing relevant features, types of subscriptions, advantages, and limitations. According to the information provided, Kahoot and Socrative are the most frequently used platforms on mobile devices, enabling users to: i) create different types of questionnaires; ii) share information on a screen for the entire class from personal devices; and iii) monitor progress in real-time, whilst obtaining immediate feedback from students. Apart from the core topics of chemical engineering, such as Kinetics, Chemical Reactors or Process Control, these platforms are commonly used to teach general, inorganic and organic chemistry and laboratory classes.

Furthermore, other advanced platforms for chemical engineering teaching were analyzed. These tools are frequently used for the preparation of: i) videos, ii) quick response codes, iii) mobile games, and iv) non-commercial and task-specific applications. This group of case studies is more frequently related to core courses of the chemical engineering curriculum since the design of applications for more specific areas of teaching requires a major effort.

According to the literature analyzed, the vast majority of case studies reported satisfactory feedback and positive effects on the learning process in chemical engineering subjects, with increased student participation and collaboration, and simultaneously, an improvement in their academic performance. Hence, the authors of this manuscript encourage the conduct of further studies for the assessment of the benefits and limitations of the use of mobile devices in chemical engineering studies, considering the feedback of students involved in the learning process and establishing different quality criteria to assess more suitable scenarios for the implementation of M-learning methodology.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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