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3D Printing Technology in Education and Some Examples of 3D Printer Technology Materials Applied in Chemistry Education

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ABSTRACT

Technology affects and changes our lives day by day. The application of technological developments and advances in education is of great importance in order to bring targeted behavior to individuals. One of the technologies we observe in many areas, including education, is three-dimensional (3D) printing technology. Three dimensional printers can be used in the field of education to better visualize complex structures. 3D printers have a truly groundbreaking technology in solid modeling. With this technology, individuals can realize their dreams in a short time and in a concrete way. 3D printing technology also shows tremendous potential in the chemical sciences. This type of technology has begun to enter chemistry education on a wide range of subjects, and chemistry models produced in educational processes such as symmetry and point group theory, unit cell theory, orbital theory and structure-energy relationships contribute to students in terms of vision, touch and detailed examination. In this study, together with general information about the use of 3D printer technology in education, the importance of using this technology in education and information about the materials used in the field of chemistry teaching produced with 3D printer technology are presented.

Key Words: Three-dimensional printing technology, Additive manufacturing, Chemistry education.

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Introduction

3D printing technology, also known as additive manufacturing technology, is a fascinating and new type of technology that can attract people of all ages and can change the world. 3D printing technology has been developing rapidly in recent years in many different areas such as defense, aerospace and automotive industry, visual arts, architecture, education, biotechnology and healthcare. Moreover, 3D printing technology increases its area of effect day by day. It is predicted that this technology will occupy an important place in Industry 4.0 industrial revolution applications that have been on the agenda frequently in recent years (Snyder, Trevor J., et al., 2014; Balcıoğlu, 2014; Çalışkan, 2015; Özsoy & Duman, 2017).
Significant studies and results of these studies are devoted in Researc and Development (R&D) technology in this field to develop 3D bioprinting techniques and to use these techniques to produce human skin, bone parts or complete organs that may be needed in accidents. Various projects have been carried out in this direction so far. For example, one of the topics discussed in this area is producing organs with 3D printing (Figure 1). A project led by the European Space Agency (ESA) is exploring the use of 3D bioprinting to support medical treatment of long-term space exploration and possible settlements on planets. Leading experts in the field work at ESA's ESTEC center in Noordwijk, the Netherlands. These studies are considered as an important issue that can turn into a survival issue for astronauts who will travel to the Moon and Mars in the future.

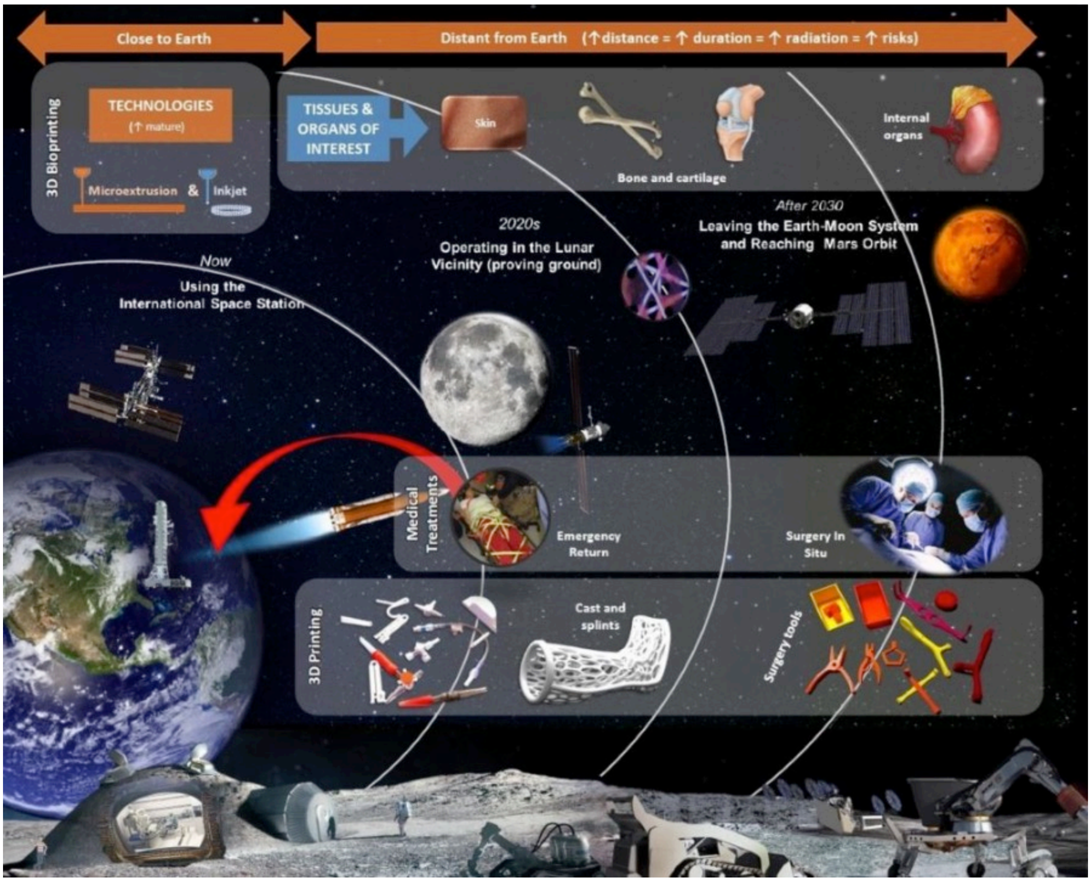


Figure 1. *Examples of 3D bioprinting studies for space studies (ESA, 2018).*

The decrease in the prices of 3D printers and the increase in the variety of materials and models have increased their usage area in the learning environments (Eisenberg, 2013; Pence, 2020). As the usability of 3D printing in education increases, it becomes a powerful resource for active learning (Fernandes & Simoes, 2016). 3D has become available to students at higher education, high school, middle and primary school levels (Eisenberg, 2013). In various educational fields (such as engineering education, science education, robotics education, special education, anatomy education, medical education, earth science education, design education, science education, STEM education, geography education, social studies education, mathematics education, geometry education) many researches and projects are being developed on 3D printers (Karaduman, 2017). The 3D printer can be used for educational purposes and as a teaching tool in laboratory projects (Isaakidis et al., 2017). In addition, 3D printing provides great benefits in the field of special education. 3D printing can serve individuals with variable abilities, including individuals with cognitive, motor, and visual impairments (Buehler et al., 2014). With the use of 3D scripts in schools, models designed on computers can be printed in 3D and turned into prototypes. Thus, theoretical knowledge can be quickly transferred to physical objects that can be touched (Lütolf, 2013). In addition, by identifying existing errors and deficiencies through prototype output, loss in time and economy can be prohibited (Gökçearslan, 2017). Pence (2020) states that 3D writing

technology can be a breakthrough in visualizing three-dimensional objects such as complex molecules by touching for individuals who are visually impaired or have major vision loss.
In this study, general information about the use of 3D printer technology will be given, based on some scientific studies on the use of 3D printer technology in education. Moreover, the importance of the use of this technology, which has become widespread in the field of education in recent years, and especially in the field of chemistry education, educational materials produced with 3D printing technology will be presented.

3D Printing Technology

3D Printer is a type of printer that produces three-dimensional objects by transferring thin layers on top of each other on a two-dimensional plane using materials such as plastic, metal, etc.
FDM (Fused Deposition Modeling) or FFF (Fused Filament Fabrication) is a technology used in three-dimensional printing technologies to create strong, durable and dimensionally stable parts with its dimensional accuracy and repeatability. 3D Printers working with FDM technology generally use thermoplastic polymer materials such as Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). The material called filament is melted with the help of a high-temperature nozzle and constructed in layers. In order to produce with 3D Printers, a 3D model is required first. AutoCAD, SolidWorks, Google Sketchup, Rhino3D are some of the tools that can be used in this field. It is possible to export models built with such software as STL files and to manufacture them with 3D printers (Tridi, n.d.).
Additive manufacturing is one of the modern manufacturing methods. Additive manufacturing is a manufacturing technique that performs the rapid manufacture of physical parts with complex geometry by adding the material layer after layer using 3D geometric data. In this technique, the part is manufactured from a 3D model obtained by different methods such as drawing with computer-aided design (CAD) programs, reverse engineering, computed tomography (CT). The 3D model is split into multiple thin layers (sliced) and manufacturing systems use this geometric data to sequentially fabricate each layer until the part is complete.
According to the working logic of the printer, the filament, which is the raw material of the printer, reaches the part called the nozzle. The nozzle, made of brass, exists where the printer's head is. When the nozzle reaches a certain temperature (at least 180□), the filament begins to melt and flow through the nozzle under the effect of the temperature. In the meantime, while the nozzle can move in the x, y and z axes to flow the substance to the desired point, in some cases the part where the filament flowing from the nozzle called the tray moves and creates an object in three dimensions. The feature of the filament is that after it melts, it spreads without touching the plate and quickly freezes and turns into a solid form. The working logic of 3D technology is explained in Figure 2.

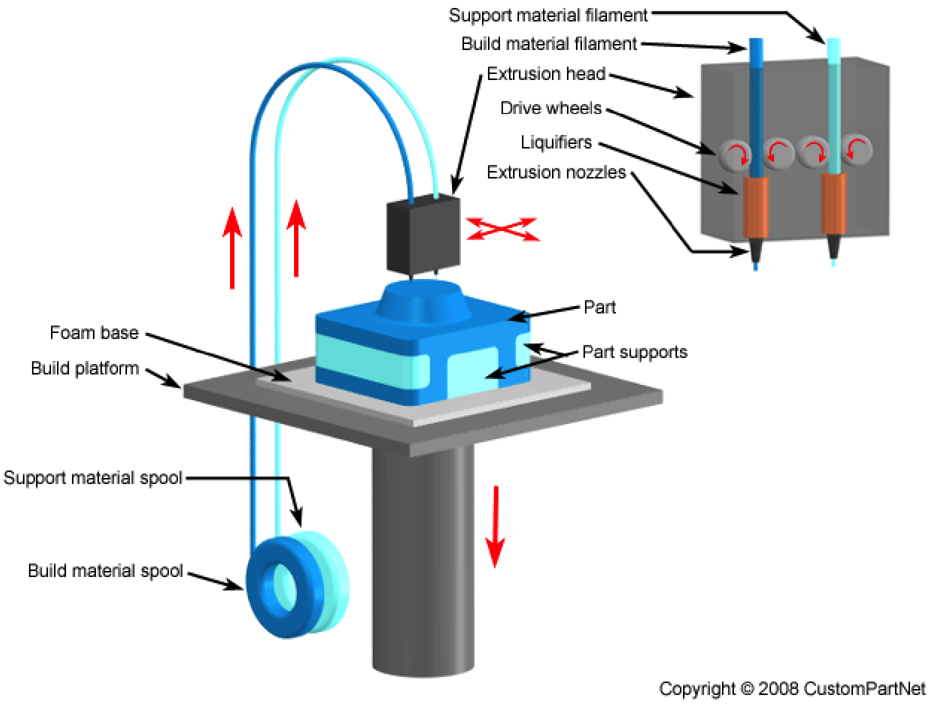


Figure 2. *3D printer operating logic (Custompart, n.d.).*

Although the method generally used is "additive manufacturing", the working principles of 3D printing technologies are not based solely on the additive manufacturing method. There are many methods used other than this method. Some of these methods are given below; (Robotistan, 2019).

- Fused Deposition Modelling (FDM)
- Stereolithography (SLA)
- Digital Light Processing (DLP)
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM)
- Electron Beam Melting (EBM)
- Laminated Object Manufacturing (LOM)

All of the 3D printing technologies provide the user with the opportunity to produce different products by using different methods. As these methods and technologies develop, 3D printing methods are evolving and easier, faster and more efficient printers are produced. 3D printers, which have become more accessible, have started to be used more frequently in learning environments.

The Importance of Using 3D Technology in Education

3D printing can be used to make STEM activities in education fun and thus to attract more interest in lessons by embodying abstract concepts. By using 3D printing in education, complex technologies can be made visible and students can be helped to design their own technologies. Through this technology, the real-life equivalents of various branches such as science and mathematics can be understood more easily. Moreover, 3d printing technology supports learning by touching and seeing by enabling students to turn the models they create with their own imagination and creativity into reality (Peels, 2017). 3D printing is a future production tool. Children who are interested in engineering and design are also the producers of the future and they should be supported to prepare their own designs and projects with 3D modeling (Eisenberg, 2013). Students will be able to develop in areas such as data synthesis, creative thinking, analytical thinking and productivity while creating their designs for 3D printers. In addition, by helping each other, students will have the opportunity to work together and improve their communication skills. 3D printing is an extremely important technology for gaining 21st century skills such as increasing student curiosity and increasing creativity (Cano, 2015). With 3D printers, meaningful learning can be achieved by concretizing many abstract concepts and obtaining in-depth and rich information. It contributes to the development of various skills in students such as problem solving, decision-making, creativity, and computer literacy (Karaduman, 2017). Since the materials obtained with 3D printing technology can be addressed to different sensory organs of students, they help complete and permanent learning in educational terms (Demir et al., 2016). As of computer-aided design knowledge will also be used in a learning environment enriched with 3D printers, students' visual media literacy can also be improved (Verner & Merksamer, 2015).

In a research performed by Ford and Minshal (2018), it was reported that "through a category selection process, five categories were found in relation to the research question of "How is 3D printing being used in the education system?"

They defined these six categories as use cases. They were:

- To teach students about 3DP.
- To teach educators about 3DP.
- To teach design and creativity skills and methodologies.
- To produce artefacts that aid learning.
- To create assistive Technologies.
- To support outreach activities

The widespread use of 3D printers has increased instructors and students' access to printing technology. These breakthroughs will significantly improve the ability of educators to design and print teaching materials in different subjects and models, and ultimately will provide new tools for students to understand important concepts, especially in science (Paukstelis, 2017).

The teaching and application of 3D printer technology in the lessons make important contributions to the educational processes in many aspects and these contributions can be summarized as follows: (Soldatov, 2015)

- It encourages students in scientific and technical creativity.
- It contributes to the development of three-dimensional design, modeling and visualization skills and abilities in students.

- It enables the creation of teaching materials in different fields from science to mathematics and history, and the teaching of subjects in an effective and efficient way with material support.
- Improves students' thinking ability to explore and create new designs
- It helps students reveal their technical skills and positively affects students' curiosity towards new generation technological products and their career choices.

Method

This study presents a review of the 3D Printing Technology and Teaching Material Samples in Chemistry Education in the literature. A review article is the summary of other researches and presenting them to the reader as a whole. A kind of literature review is made and as a result of the scanning, a general summary is written for each study and collected (Taylor and Francis, 2021). Review articles come in the form of literature reviews and, more specifically, systematic reviews; both are a form of secondary literature.

Findings

3D Printing Technology and Teaching Material Samples in Chemistry Education

Research on the use of 3D printing technologies in chemistry education has gained momentum especially after 2014. These studies generally focused on the importance of 3D printing technology in chemistry education, the design strategies applied in this field, and the way of application of this technology (Pernaa & Wiedmer, 2019).
Regarding research environments, 3D printing has been limited to biomedical applications and engineering, but has enormous potential in chemical sciences as well (Gross et al., 2014). 3D printing has begun to enter chemistry education from various angles. In recent years, 3D printing technology has been applied to teach a broad variety of subjects in the area of chemistry teaching using 3D printed models. These topics include orbital theory, symmetry and point group theory, unit cell theory, and structure-energy relationships (Dean et al., 2016). 3D configurations are a critical step for the chemistry student in understanding basic concepts such as molecular symmetry in inorganic complexes, organic compound stereochemistry, chirality and polymerized, monomer relationships with biomacromolecular structures, etc. (Paukstelis, 2017).
In our three-dimensional world, the V (x, y) graph of a function with at most two variables can be plotted, seen and understood. Therefore, even for the smallest polyatomic molecules, such as three atoms, representation of the potential energy function in all dimensions is not possible. This raises some obstacles to understanding the interactions of atoms within a molecule. In a study, the isoenergy approach that allows the potential energy function of a molecule with three atoms to be displayed in 3D space, not as a surface, but as a volume, has been reviewed. In addition, the use of 3D printing technology has been proposed to create plastic models of such isoenergy objects that can be captured and studied in detail (Teplukhin & Babikov, 2014).

Concrete models help to visualize three-dimensional chemical structures for students and researchers. 3D printing technology is a special and easy approach to the development of molecular 3D models (Scalfani & Vaid, 2014). Direct interaction with physical 3D models provides significant improvements in education (Paukstelis, 2017). 3D crystal models, both virtual and printed, will help students and teachers interact with issues in chemical education such as symmetry and point groups (Casas & Estop, 2015). With 3D printing, molecules directly from a digital 3D template can be produced in one piece, significantly simplifying the development process of molecular models. The desire to create a collection of classic and exotic chemical structures that have been forced to be depicted by conventional manufacturing methods or commercially available model kits has motivated the interest in 3D-printed molecules. From simple organic structures to coordination compounds and enlarged solid structures, any model can be designed with 3D printing technology (Scalfani & Vaid, 2014).

For several years, tangible models have become a main component of chemistry education for students' three-dimensional representation of chemical structures. (Jones & Spencer, 2017). 3D representations of chemical structures have been used for decades in chemistry research and teaching, in the form of concrete models (Scalfani & Vaid, 2014). The types and precision of bonds and structures that can be used in the arrangement of molecules limits conventional chemistry simulation kits (Jones & Spencer, 2017). The representation of complex molecules by traditional techniques is often difficult. The majority of manufacturing methods are system-specific, which means they represent a certain class or category of chemical structures successfully but do not create a variety of chemical structures. 3D printing is a new method in which conventional molecular model structures can solve the above-mentioned limitations (Scalfani & Vaid, 2014). The recent advancement of 3D printing technology has allowed a much wider range of teaching molecules to be developed (Jones & Spencer, 2017). Multicolored and tangible chemistry models could be produced using 3D printing software (Wieren et al., 2017).

In the study by Scalfani and Vaid (2014), 18 molecules and 7 expanded solid materials were printed with 3D printers. The study suggests convenient ways to prepare 3D printable digital files of chemical structures, and the study results show that 3D printing is an excellent method for producing 3D molecular models and enlarged solids. The models help students and researchers imagine three-dimensional (3D) chemical structures and provide a specific and simple approach to the development of 3D plastic models of molecules and enlarged solids. In this study, a set of molecular structures that will be useful for teaching chemical education topics such as symmetry and point groups are prepared for digital 3D design. In addition, two main preparation methods showing how to prepare 3D printable chemical structures are discussed. From the prepared digital 3D chemical structure series, 18 molecules and 7 expanded solids were 3D printed. Several challenging structures such as ferrocene, [B12H12] -2, ZnS and CaF2 were easily fabricated (Figures 3 and 4).

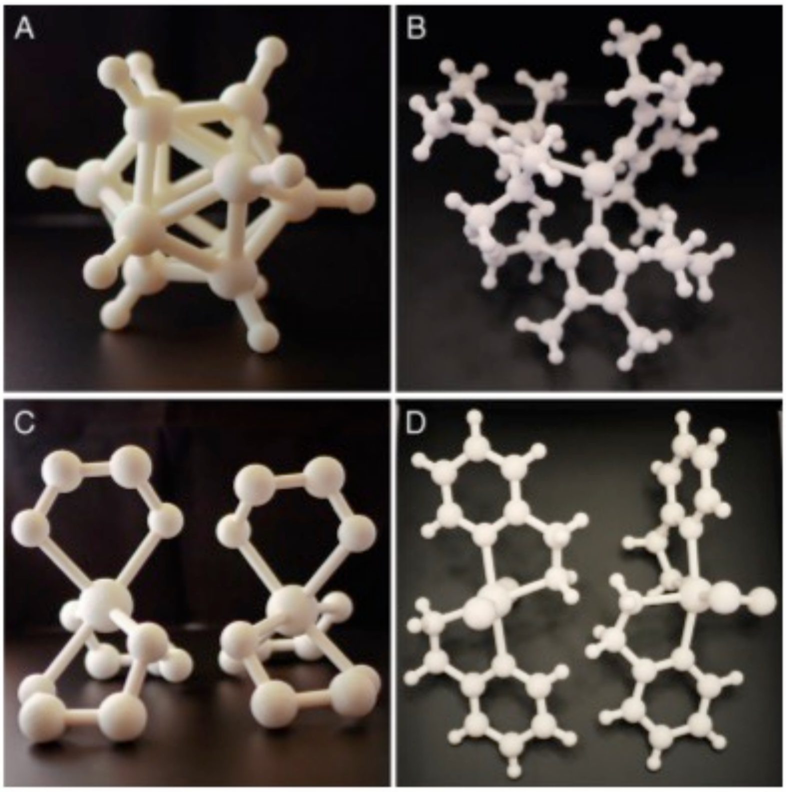


Figure 3. *Representative examples of 3D-printed molecules: (A) $[B_{12}H_{12}]^{2-}$, (B) $[Ge(iPr_2NHC)_3]^{2+}$, (C) Δ-$[Cd(en)_3]^{2+}$ and Λ-$[Cd(en)_3]^{2+}$, (D) Trans- and cis-$[FeCl_2$(2-(aminomethyl)pyridine$)_2$. (Scalfani & Vaid, 2014).*

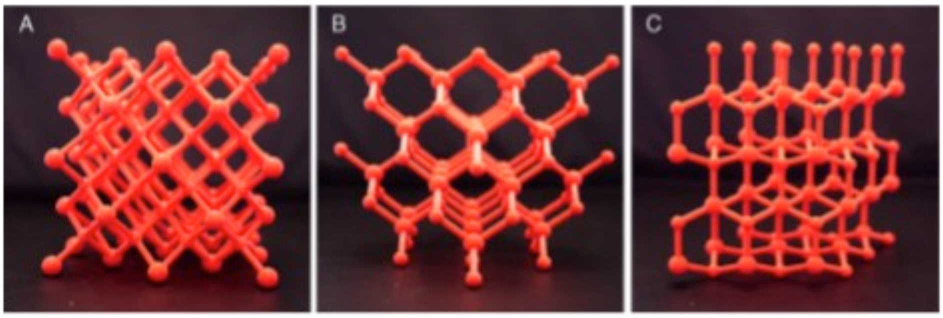


Figure 4. *Representative examples of 3D printed solids: (A) CaF_2, (B) ZnS mineral and (C) ZnS hexagonal crystal structure (Scalfani & Vaid, 2014).*

In another study conducted to be useful for educators working in the field of polymer education, students studying polymer, and researchers in the field of polymer science and nanotechnology, several block copolymer (BCP) nanostructure morphologies were designed and concrete 3D prints were produced (Figure 5). For 3D printing, very few periodic nanostructure 3D models are available, unlike molecular and extended solid chemical structures. To overcome this, a number of 3D nanostructure digital models have been created using various methods. Successful 3D prints of nano structures were produced in the study. Such nanostructure models find wide application in the teaching and study of nano technology (Scalfani et al., 2015).

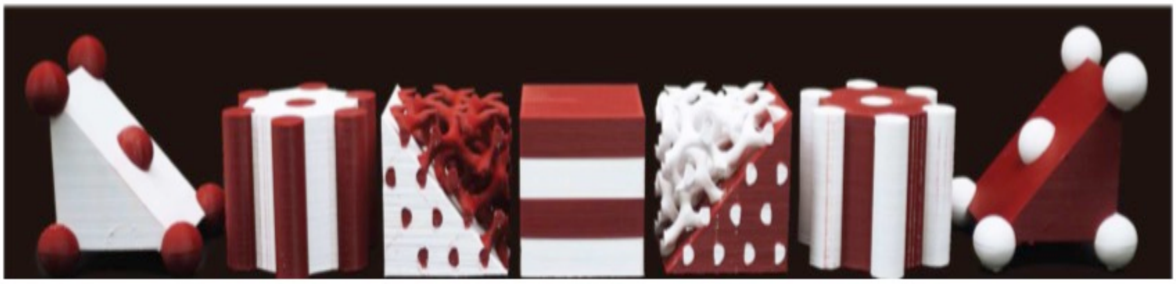


Figure 5. *3D printed AB diblock copolymer morphologies (Scalfani et al., 2015)***.**

Rossi et al. (2015) proposed a software used to teach chemical education subjects which enables the creation of three-dimensional customized structures. One of the most important features of the software is that the models created can be printed by a low-cost 3D printer. Color input geometries can be obtained with the use of free licensed and multi-platform applications with a simple click-change procedure to build .obj and .mtl files. A series of simple processes are presented to transform chemical structures in 3D printable models. This method requires no specific knowledge of programming and helps students and educators to understand and envision structural features such as isomerism, conformers, processes of reaction, point groups, and chirality (Figures 6 and 7).

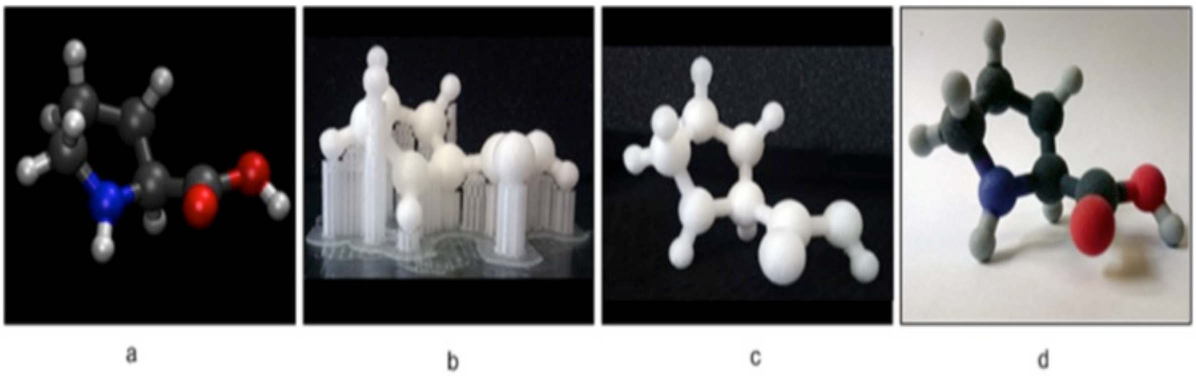


Figure 6. *(a) 3D geometry of L-proline displayed in VDM, (b) Structure printed with a FFF 3D printer with supports, (c) Structure after removal of supports, (d) Color model obtained (Rossi et al., 2015).*

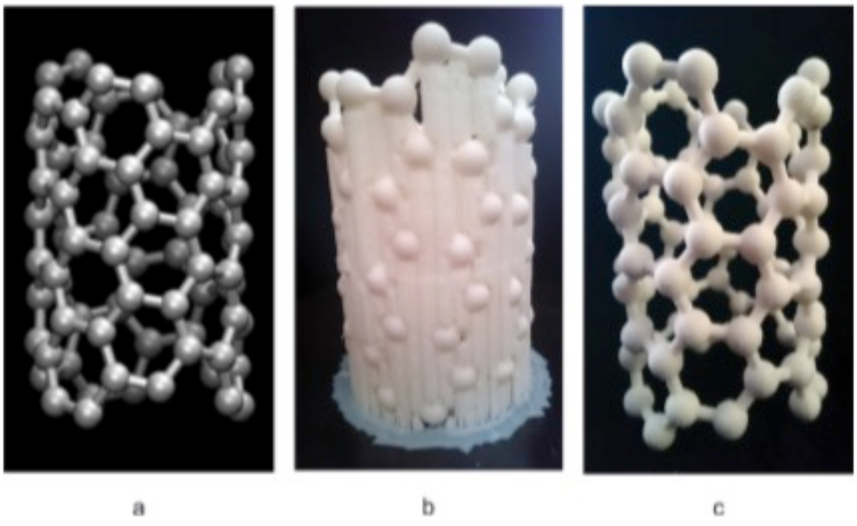


Figure 7. *(a) 3D geometry of a nanotube displayed in VDM, (b) Structure printed with a FFF 3D printer with supports, (c) Structure after removal of supports. (Rossi et al., 2015).*

Printed 3D crystal models will assist students and teachers with subjects such as symmetry and point groups in chemical education. In the study of Casas and Estop (2015), the use of 3D printing to produce concrete crystal models was examined, and as an example of a 3D design application to examine point-symmetry, two free downloadable tools (interactive PDF files and a mobile application) are presented. In their classes, educators are expected to be motivated to use the tools provided, and the work is expected to inspire other university educators to design and share similar instruments (Casas & Estop, 2015).

Orbit theory offers a strong tool in chemistry for embodying and explaining many phenomena and concepts. Students are exposed to atomic and molecular orbitals in the form of two-dimensional sketches in several "introduction to chemistry" courses. In the study by Robertson and Jorgensen (2015), a general method for generating 3D printing files of orbit models to perform electronic structure calculations and molecular visualization is described. Methods have been developed to produce both an informative and structurally robust model, both solid and lattice orbitals. Numerous examples of various interesting physical printing systems are also given in the 3D printing .stl format and as a completely illustrated tutorial for the process.

Handling basic physical chemistry concepts such as potential energy surface, transition state, and reaction pathway is a difficult challenge in chemistry teaching. The traditionally used, over-simplified, 2D representation of potential and free energy surfaces makes this task much more challenging and confuses students. In a study (Kaliakin, et al., 2015), surface models of this 2D representation were created using 3D printing technology. Printed models include potential energy surfaces for the rotation of methyl groups in 1-fluoro-2-methylpropene calculated using the hydrogen exchange reaction and quantum chemical methods. In addition, several model surfaces created from bivariate analytical functions are presented and how these 3D models can be used in teaching different chemical kinetic, dynamic and vibrational

spectroscopy concepts such as potential energy surface, transition state, minimum energy reaction path, reaction trajectory, harmonic frequency.
In a study on the application of 3D printing technology to VSEPR theory teaching (Dean et al.2016), students were provided with two-dimensional templates that allow 3D printing pens and basic VSEPR shapes to create three-dimensional ABS models. 3D printing pens are a potentially powerful tool for teaching VSEPR theory. There are 13 frequently encountered VSEPR geometries. Interestingly, it was found that when the experimental group allowed to draw whatever they wanted; the majority chose to draw a trigonal bipyramide. The experimental group, consisting of first-year students working in groups of two, produced only one or two models of higher difficulty levels within the allotted 60 minutes. While the commonly used ball and stick models are an important medium to teach the theories of VSEPR, the use of 3D printing pens allows students to learn about molecular geometries in a new and special manner. Not only is this a fun and interesting learning exercise for students, the models obtained can also be used by students at later stages. This condition was expected to lead to a better mindset for students to study the VSEPR theory and to share their encounters with their friends. The study designed a 2D prototype to encourage student drawing. The 3D printing pen allowed students to process through the images and eliminate the need for strong artistic skills to generate model output. The shapes obtained using the digital 2D stencil should be like puzzle pieces in which the students sketch the two pieces and then connect them to each molecular shape by using the 3D printer pen. (Figure 8). The student then preserved the fragments and joined them with the pen. The effect is a vibrant 3D model of basic VSEPR shapes (Figure 8).

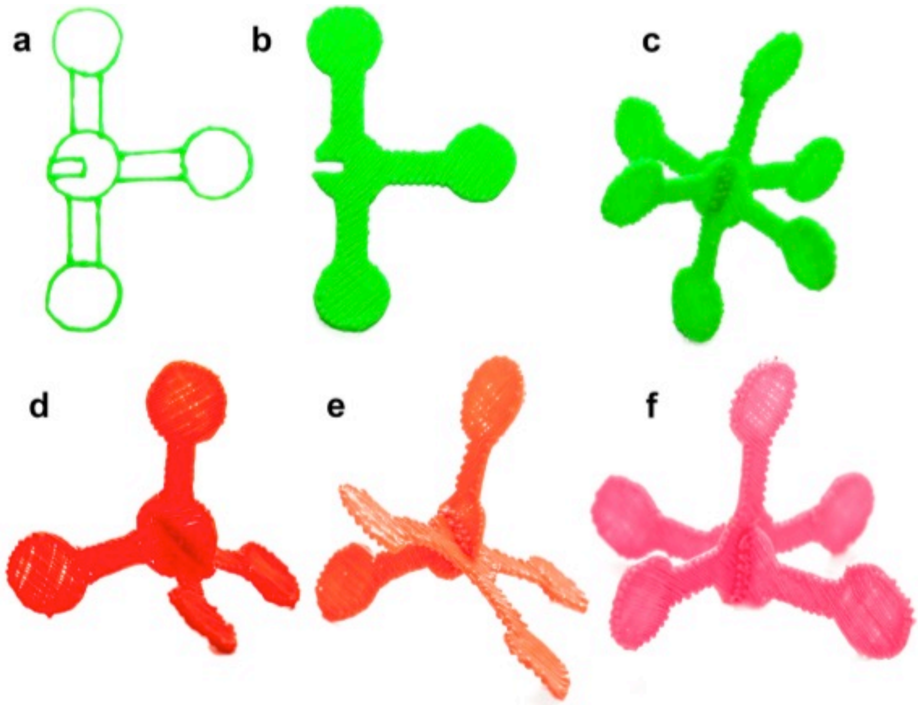
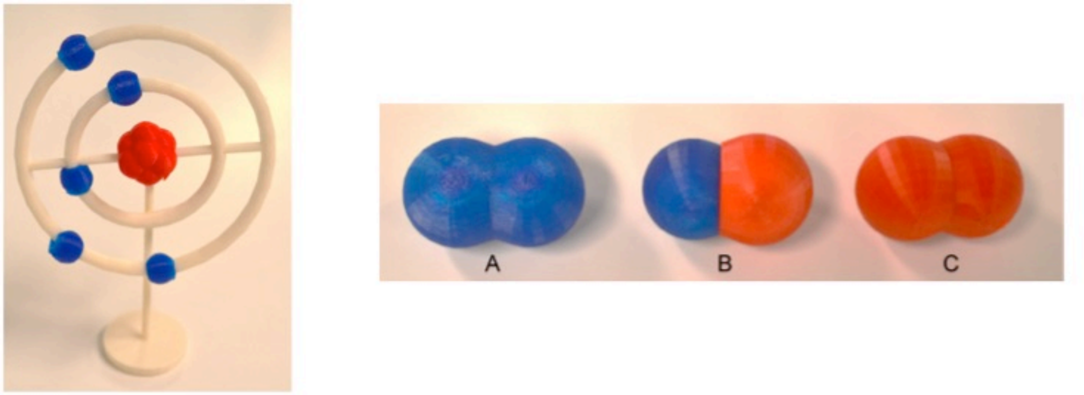


Figure 8. *Three stages of octahedral pattern construction from template: (a)Template, (b) Filling, (c) Assembly. Examples of products obtained: (d) Regular tetrahedron, (e) Triangular bipyramide, (f) Square pyramid (Dean et al. 2016).*

In a study by Smiar and Mendez (2016), three sets of physical models were created using 3D printing for a chemistry lesson (Figures 9 and 10). In the first semester of introductory chemistry courses, the Bohr atom model, bond polarity and hybridization were common subjects and were chosen for this research. All three of these subjects focus on three-dimensional atoms and molecules which, with two-dimensional images or molecular model kits, cannot be completely represented. For teaching some subjects, the interactive model set on the Bohr atom model, bond polarity and hybridization issues has proven to be a useful tool. In addition, the results obtained from student questionnaires showed that these models, which are easy to produce, have a positive effect on students' perceptions of learning. Increasing access to 3D printing means that in chemical education, this modern technology will play a very important role.



(I) (II)

Figure 9. *(I): 3D printing of boron element according to Bohr atom model; (II): (A) Nitrogen (N_2) molecule, (B) Nitrogen monoxide, (C) Oxygen (O_2) molecule (Smiar & Mendez, 2016).*

Figure 10. *Propene model made with hybridization model kit. Sigma bonds are purple, pi bonds are orange, carbon atoms are black, and hydrogen atoms are white. (Smiar & Mendez, 2016).*

In a study by Griffith et al. (2016), 3D hydrogen orbital models were created by 3D printing (Figure 11). Students frequently have trouble visualizing 3-dimensional forms of hydrogen electron orbitals without the help of physical 3D models in an introductory course in chemistry. Models available commercially are also very costly. 3D printing provides a solution to produce orbital models of hydrogen. The creation of models requires plotting the electron trajectory probability distributions in spherical coordinates and exporting them as stereolithography (.stl) files (a common format for 3D printing). There are both free (CalcPlot3D) and licensed software (Matlab, Mathematica, Maple) that can draw orbital equations and export them in the desired format.

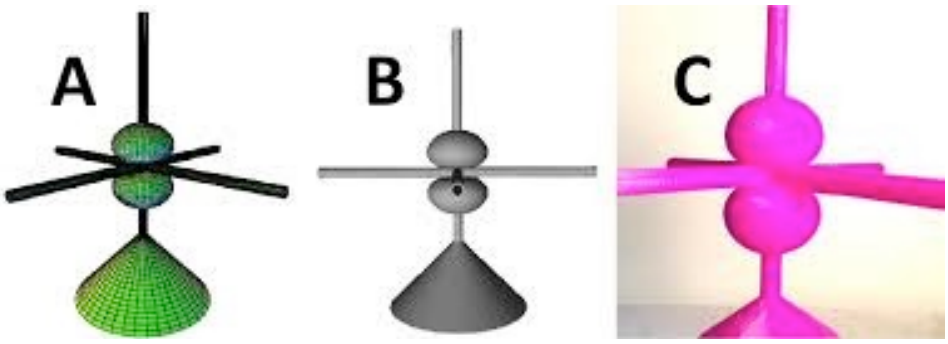


Figure 11. *Creating a 3D printed model for a 2py orbit. Panel A is the orbital model prepared in CalcPlot3D. Panel B represents the .stl file as seen in the free online STL viewer used to check the .stl file output from CalcPlot3D. Panel C is the physical 3D printed model of the 2py orbit (Griffith et al., 2016).*

In the study conducted by Penny et al. (2017), stereochemistry, isomerism, hybridization and orbitals issues were included, and three-dimensional orbital kits and molecular models were created (Figure 12). In this study, a modularly adjustable molecular model and orbital kit was developed, this kit was produced using 3D printing and used in teaching stereochemistry, isomerism, hybridization and orbitals. Using this technology, atoms with sp3, sp2 and sp hybrid orbitals (carbon, oxygen and nitrogen), hydrogen atoms, bonds (single, double, triple and rotatable) and clips to join these parts have been developed and printed. 3D printing has been used to create modular molecular and orbital models. In addition, models have been designed to illustrate basic concepts in stereochemistry, configuration, and hybridization.

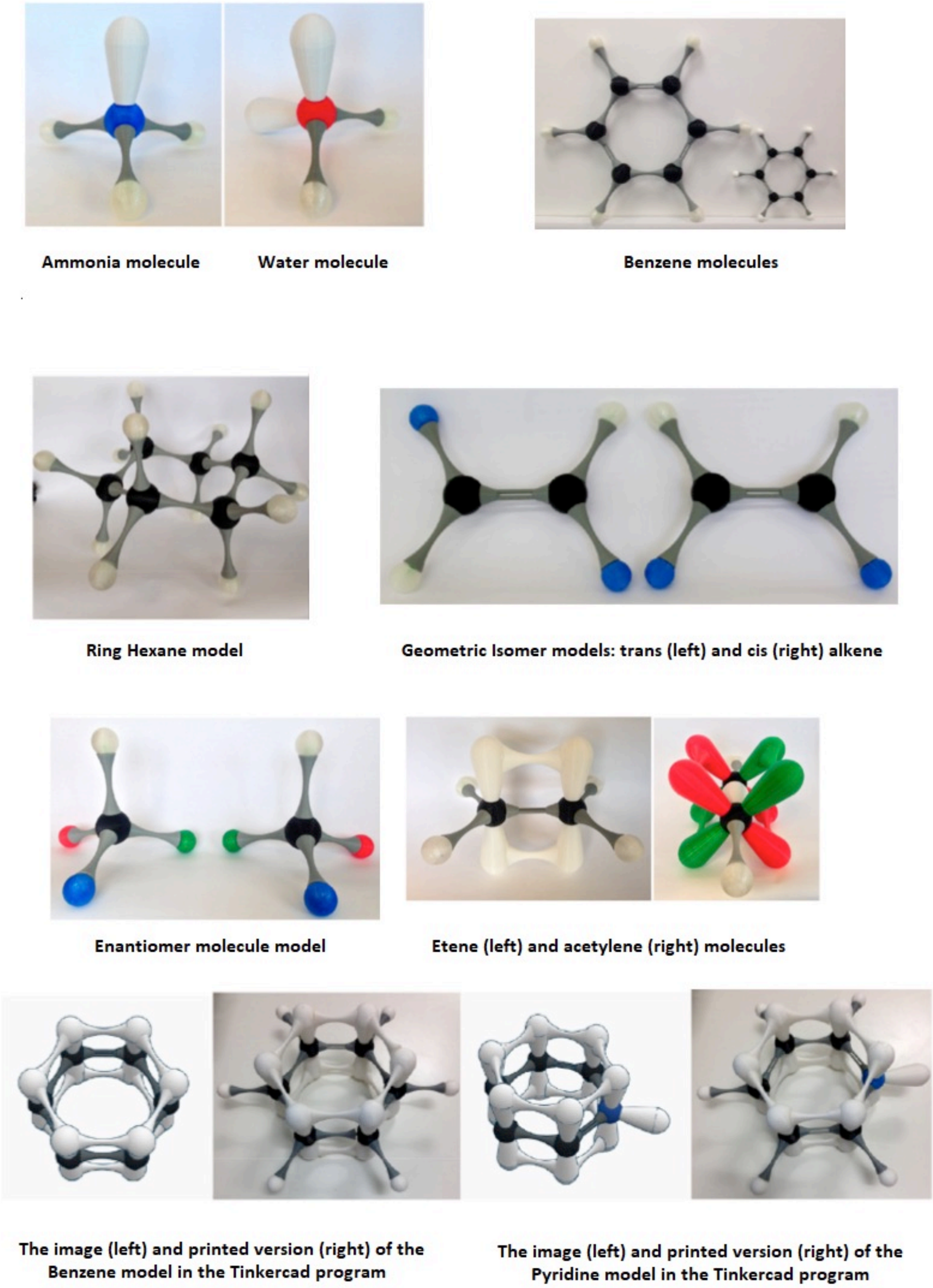


Figure 12. *Various molecular models and orbital kits prepared with 3D printing technology (Penny et al., 2017).*

In another research performed by Van Wieren et al. (2017), 3D structure samples from organic chemistry, organometallic chemistry and biochemistry were presented (Figure 13). In this study, the use of color 3D printers as a visualization tool is explained and, information is given about the method of generating concrete models for chemistry and biochemistry teaching applications using Chimera and Magics molecular visualization and 3D printing software.

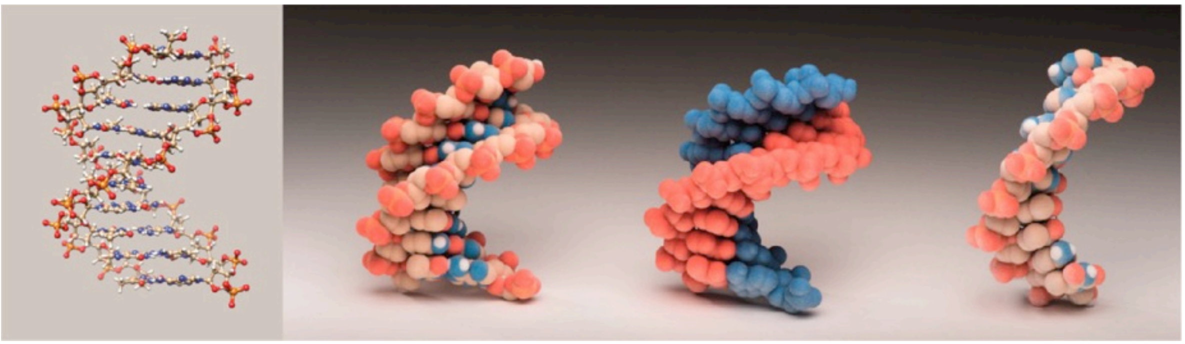


Figure 13. *3D structure examples from Organic Chemistry, Organometallic Chemistry and Biochemistry using Chimera and Magics molecular visualization and 3D printing technology (Van Wieren et al., 2017).*

Concrete models in chemistry curriculum have been used for several years to help students imagine chemicals in three dimensions. In these structures, the types and exactness of the bonds are critical to create accurate models. With the advancement of 3D printing technologies, a broader spectrum of molecules has become available. There are nevertheless a variety of technical difficulties in printing molecular structures. For example, many technically complicated and not always user-friendly software applications have to be used. A research by Jones and Spencer (2017) shows an easy way of producing the files needed to print practically every 3D molecule. Numerous basic molecular structures can be easily obtained online from databases such as UniProt or PubChem. The study investigated the possibilities of printing models using online and local companies and in-house 3D printers. It has been stated that in this way, 3D printing will be accessible to a wider audience. Moreover, it is claimed that it can be helped to spread its use in chemical pedagogy and can be used in students' learning exercises.

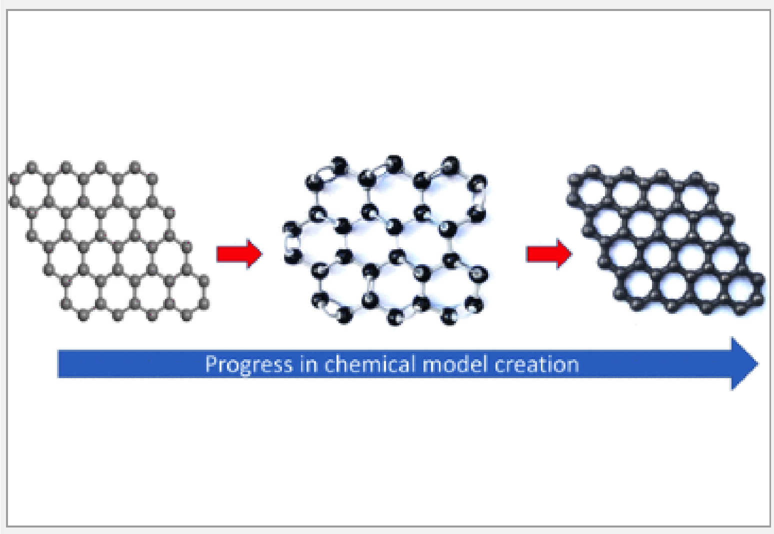


Figure 14. *Progress processes in creating chemical models in 3D printing technology (Jones & Spencer, 2017).*

In a study performed by Paukstelis (2017), he explained the MolPrint3D program with various examples (3-dimensional structure of cis-1,2-dimethylcyclohexane and trans-1,2-dimethylcyclohexane molecules, etc. (Figure 15)). The increased availability of non-commercial 3D printers has given greater access to printing technology for teachers and students. However the printing of complex molecular structures in balls and sticks is faced by different obstacles, including the need for molecular complexity support structures. MolPrint3D is a Blender 3D modeling software plug-in that increases molecular printability by permitting the consumer to selectively break down molecules. MolPrint3D attaches pins to bonds and holes within the atom at the chosen attachment points, so that pieces can be printed and assembled individually. This technique decreases the number of supporting structures necessary and allows the creation of large macromolecular structures as ball and stick models, and MolPrint3D offers a simple and intuitive way to simplify 3D printing molecular ball and clamp models. Splitting models into tiny parts that can be assembled easily after printing simplifies the minimization of costs, reducing the need for full support systems and improves the ability to print multiple models with one printing session. These innovations intend to significantly enhance teachers' capacity to print molecular templates for all classes and ultimately offer new tools for students to grasp critical chemistry concepts.

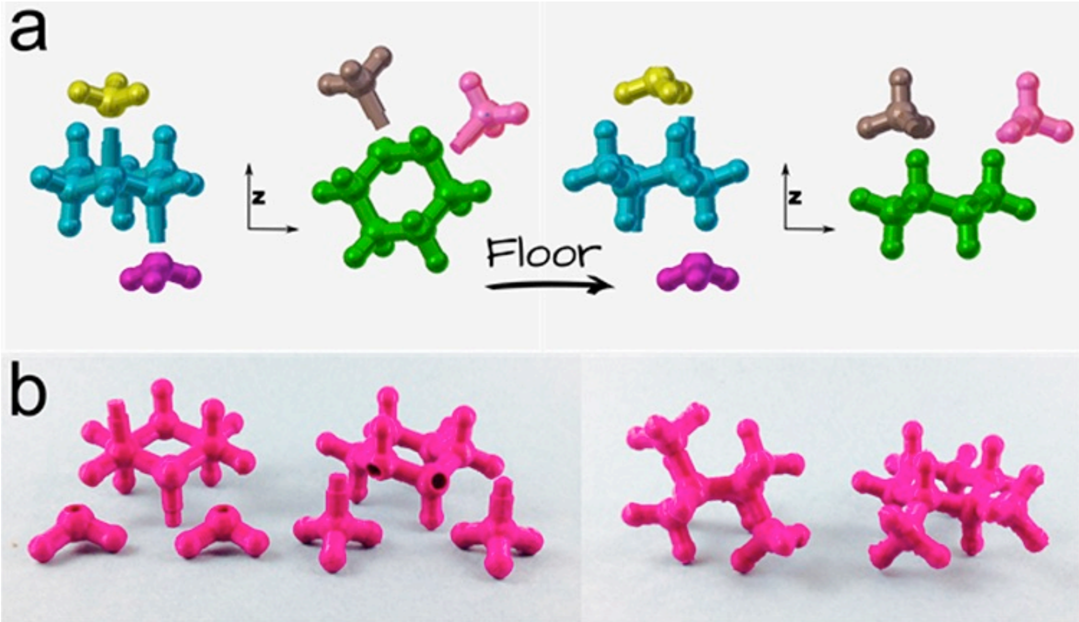


Figure 15. *1,2-Dimethylcyclohexane structures. Axial (blue, yellow, purple) and equatorial (green, gray, pink) conformers were included in substitution (connected) groups. (b) completed printed models (Paukstelis, 2017).*

In another research by Carroll & Blauch (2018), π-bonded models with embedded magnets were produced using three-dimensional printing technology. This model enables students to have a kinesthetic experience that imitates the force of p-orbital interactions that are bonding, linking, and non-binding (Figure 16).

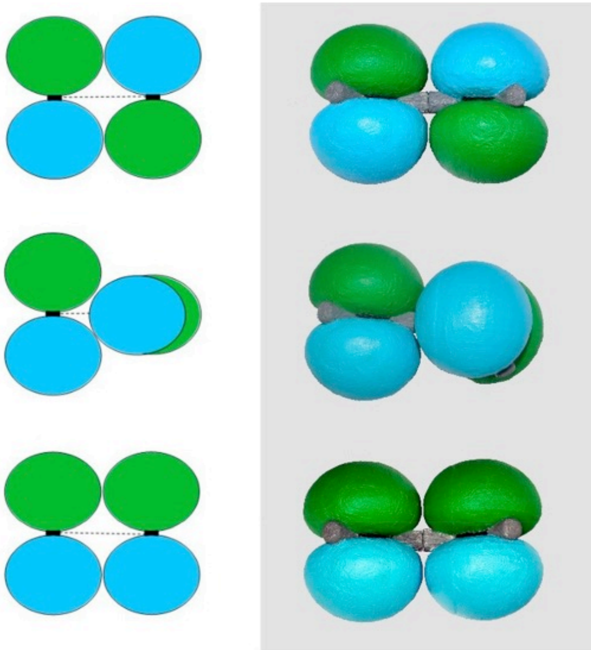


Figure 16. *P-Orbital array line representation (left) and 3D-printed bonded (bottom), non-bonded (center), opposing linker p-orbital interactions (Carroll & Blauch, 2018).*

Some hybrid orbital models were produced by de Cataldo et al. (2018), using 3D printing technology. The concept of hybrid orbitals is seen in the transition from atomic orbitals to molecular bonds in chemistry course. Both physical models of individual hybrid orbitals and combinations of hybrid orbital types have the potential to aid in visualizing molecular geometry. The use of a freely available JavaScript application (CalcPlot3D) enabled the creation of 3D print files (.stl /.3mf files) that can then be printed to a 3D printer. This procedure is low cost, and with this approach, mathematically precise hybrid trajectory models can be generated that can function as applied pedagogical tools.

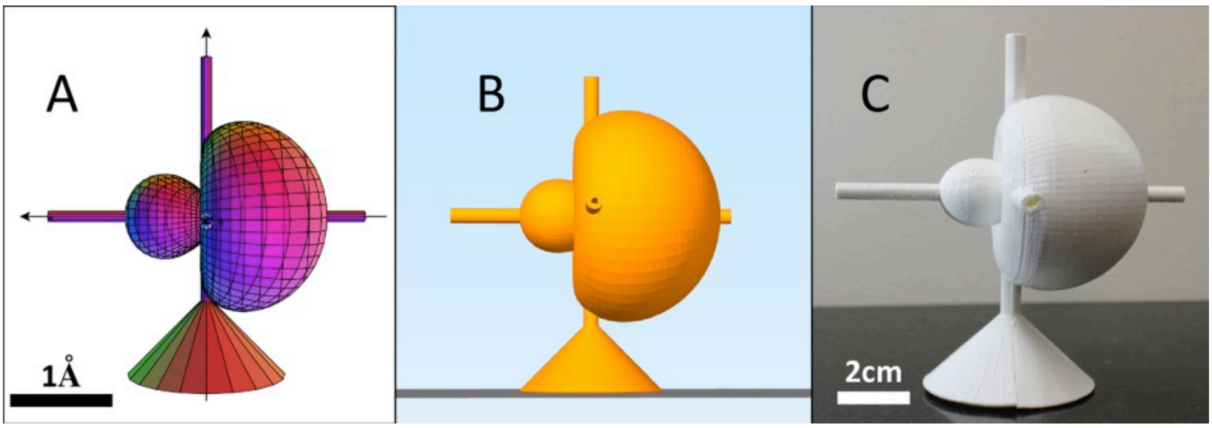


Figure 17. *Three stages of the 3D printing process. (A) sp^2 graph. A hybrid orbit in CalcPlot3D with three axes and a conical base. (B) .Stl file repaired for the same hybrid orbit in Simplify 3D, a program that converts .stl files read by 3D printers into .gcode files. (C) Fully printed physical sp^2 orbit (de Cataldo et al., 2018).*

Bernard & Mendez (2019) suggested the use of pen-like 3D writing products called "Handheld 3D Printer" or "3D Pen" in creating geometric structures, considering the long product acquisition time in conventional 3D printers and therefore very difficult to integrate into the course period. However, they stated that these pen-like products should be supported with templates created with classical 3D printers because it is difficult to make 3D drawings directly. His studies, in which classical 3D printers and pen-like 3D printers were used together, provided a different perspective to the use of 3D printers in chemistry education. Figure 18 shows how the template created with 3D printing technology is used to create a methane molecule model with 3D Pen. The modular structure used can provide a basis for the creation of very different and complex molecular models by combining the templates in different ways. Figure 19 illustrates the use of the thus generated template for the toluene molecular model.

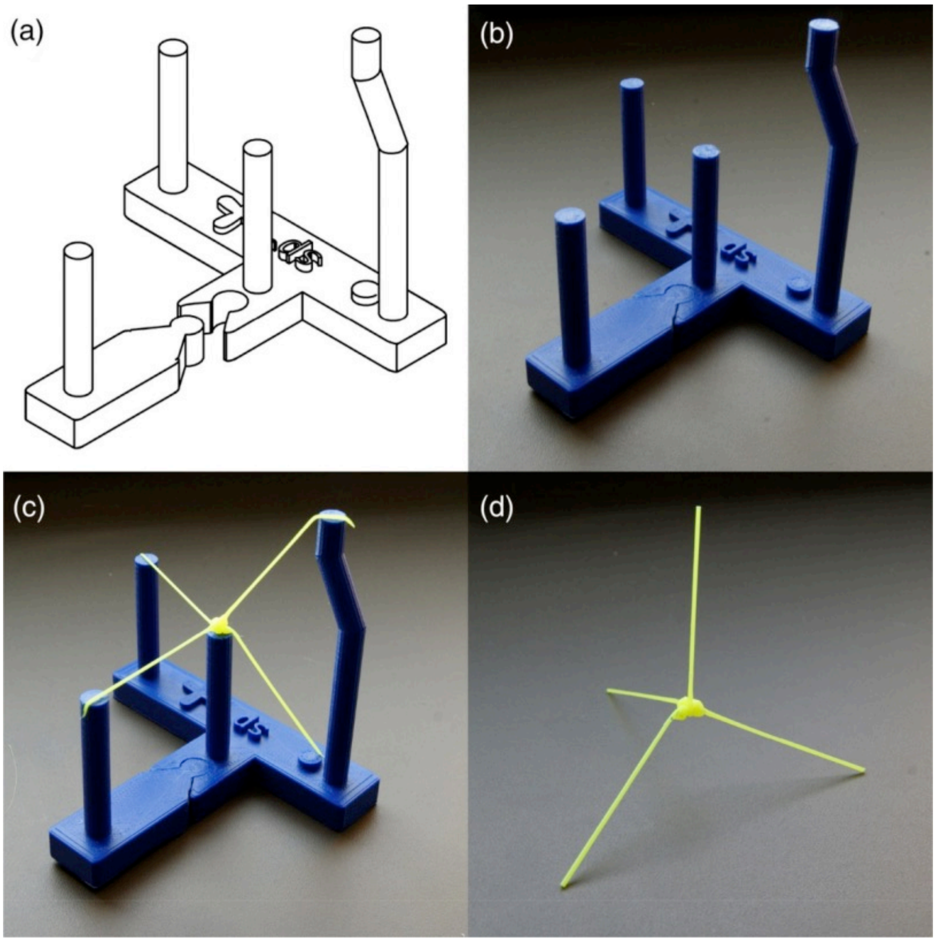


Figure 18. *Creation of the methane molecule model with the 3D Pen (Bernard & Mendez, 2019).*

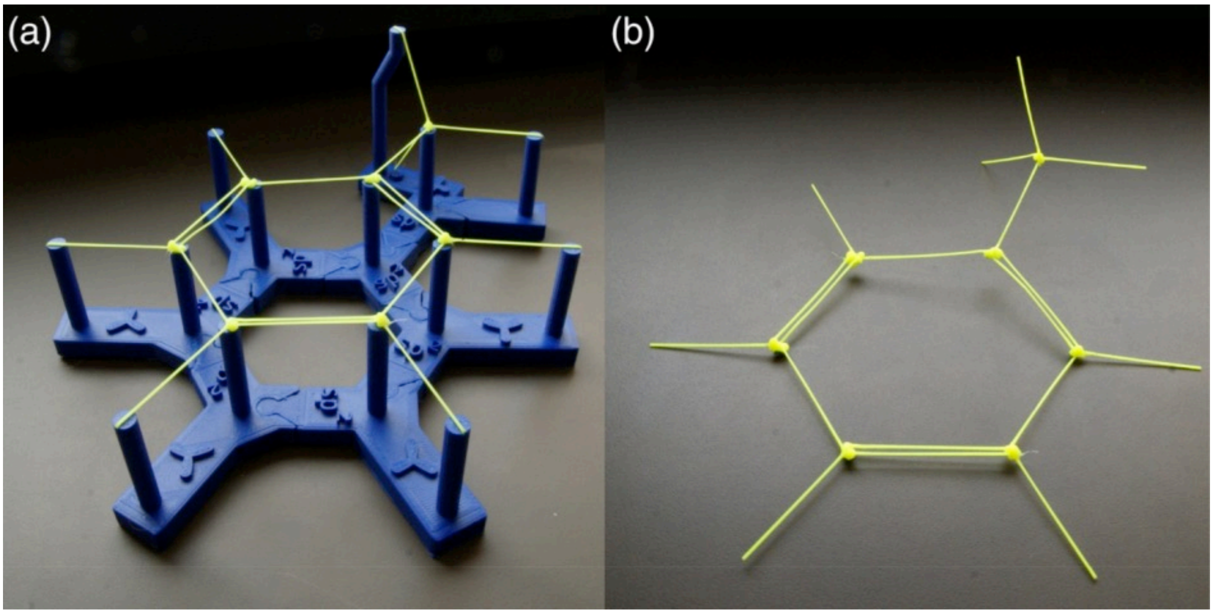


Figure 19. *Establishing a toluene molecule model with 3D Pen (Bernard & Mendez, 2019).*

In an ongoing study by Şimşir (2020) in Turkey, 3D designs were made using the Tinkercad program related to Atom and Molecular Structures and Chemical Bonds, which are covered in the Chemistry course, and these designs were printed. With this study, it was aimed to transform abstract chemistry subjects into concrete by using 3D printers and it was thought that this would contribute to the realization of permanent learning by increasing the motivation of the students. In this context, 3D materials on atom models, layer electron distribution, Lewis structure, change of periodic properties, crystal lattice structure of ionic compounds included in the 9th grade chemistry curriculum were designed and printed (Figures 20-24).

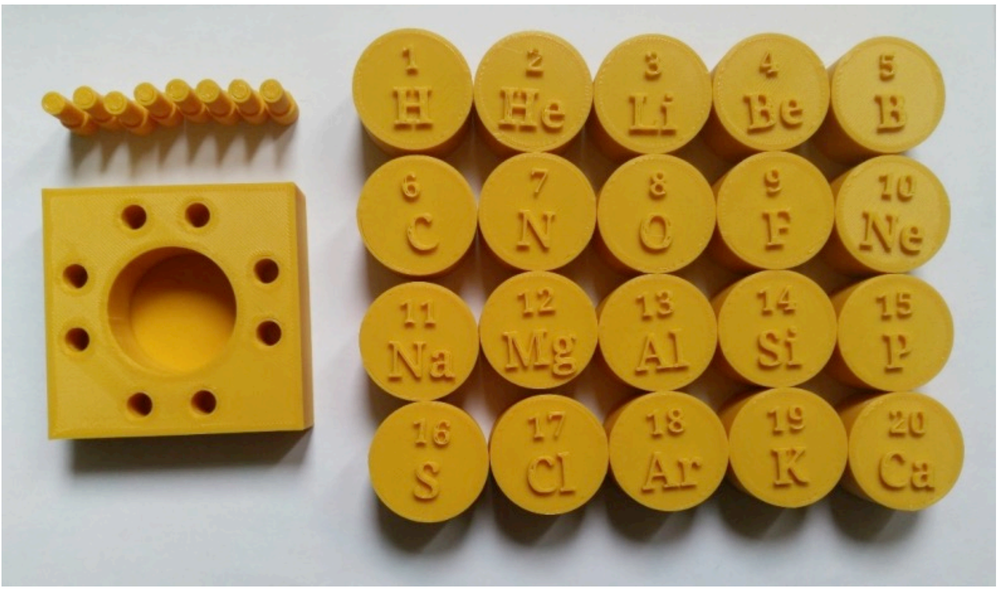


Figure 20. *3D material on the topic of Lewis structure (Şimşir, 2020).*

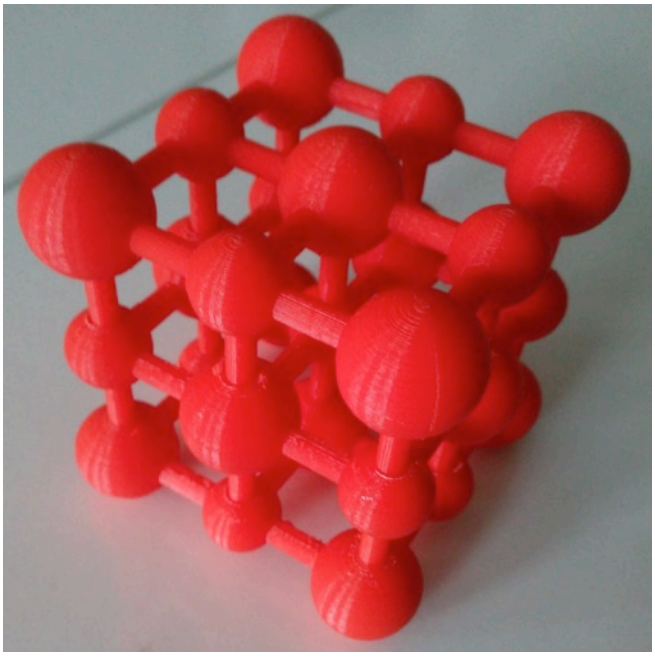


Figure 21. *NaCl compound ionic lattice structure model (Şimşir, 2020).*

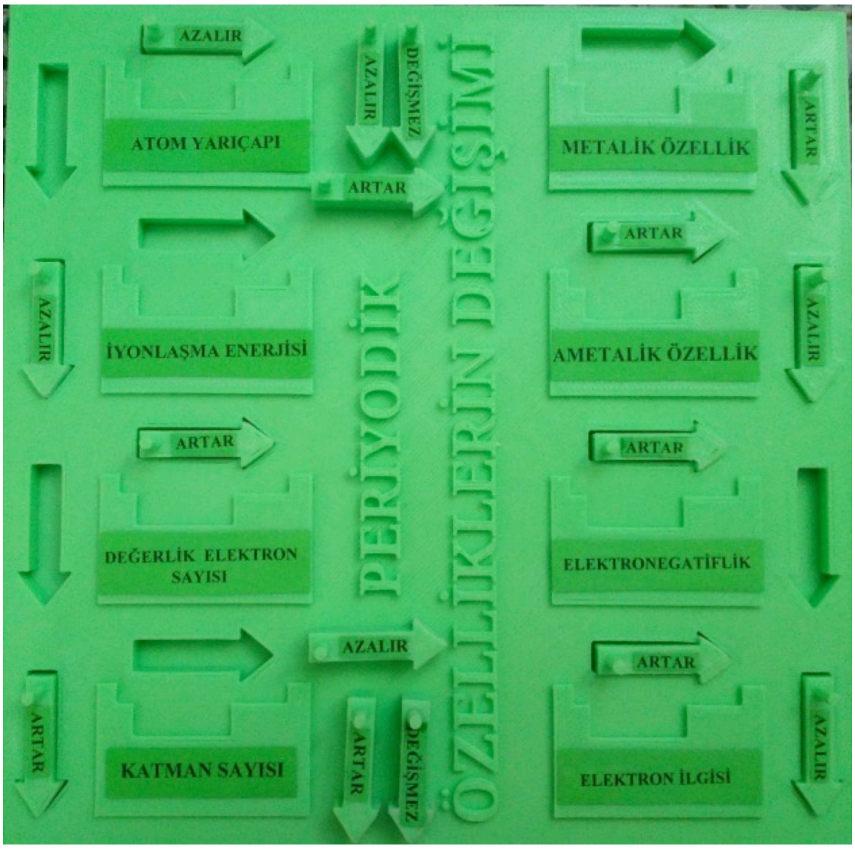


Figure 22. *3D material on the subject of changing periodic properties (Şimşir, 2020).*

Figure 23. *3D material on the subject of layer electron distribution (Şimşir, 2020).*

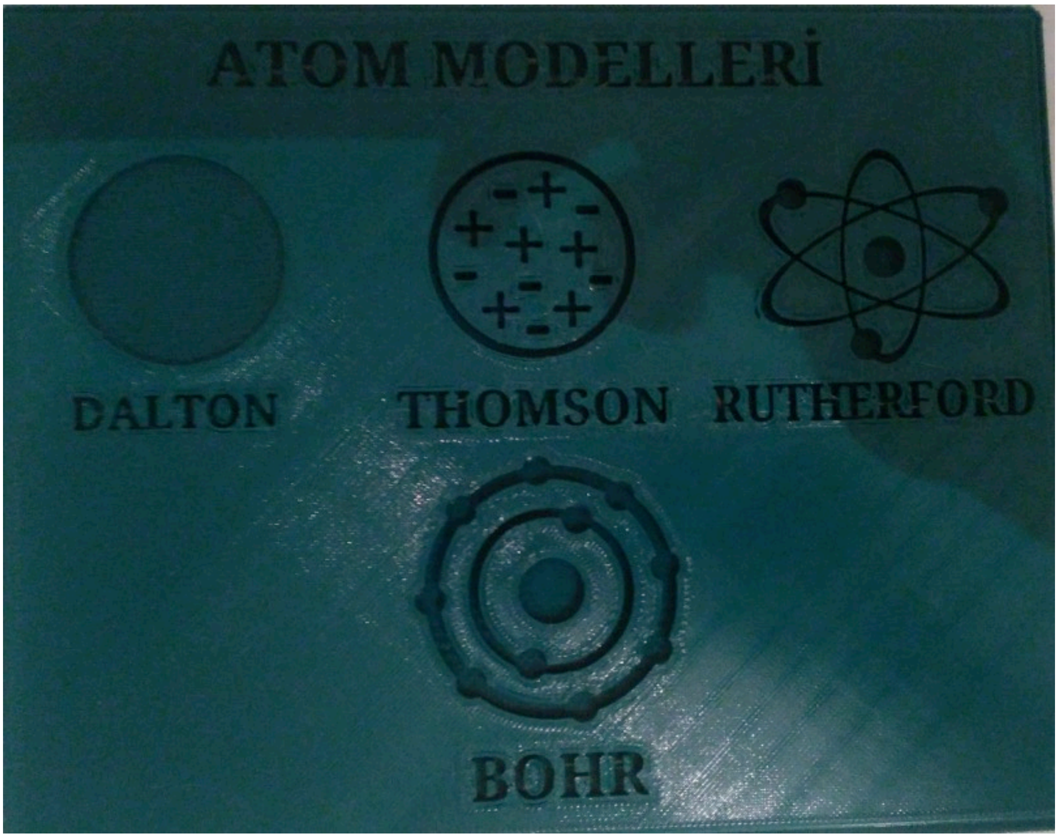


Figure 24. *3D material on the subject of atomic models (Şimşir, 2020).*

Dıscussıon, Conclusıon and Recommendatıons

In the literature about the use of 3D printer technology in chemistry education, it has been stated that 3D technology in chemistry education enables the visualization of abstract objects effectively. It has been emphasized that chemistry education with the produced materials can make great contributions in terms of being more efficient and the taught knowledge to be more permanent. Chemistry models produced during the education process help students in terms of both seeing and touching and detailed examination. It provides support to educators especially in teaching abstract subjects. In the education process supported by this technology, students can also have the opportunity to develop in many areas such as data synthesis, creative thinking, analytical thinking while creating their designs for the 3D printer.

In recent years, instructors and students have increased access to 3D printing technology. These improvements can significantly enhance the technical skills and abilities of instructors at the point of pushing models that can be used in chemistry education for all classes, and provide students with new tools to understand important chemistry concepts. In addition, with this technology, instructors can have the opportunity to offer their students individualized learning environments. It is thought that the materials obtained with 3D printing technology will help students to learn fully and permanently in terms of education, since different sensory organs can be addressed.

A project has been implemented to establish technology workshops across the country in Turkey, recently. The aim of the project is to establish 100 technology workshops named DENEYAP to cover all 81 provinces. Institutions T.R. Ministry of Industry and Technology, T.R. Ministry of Youth and Sports, TUBITAK and Turkey Technology Team cooperate for the realization of the project (Deneyap, n.d.). It is planned to carry out science and technology-oriented applied studies in DENEYAP workshops. It is expected that these studies will make significant contributions to the education and training process. Thus, these studies can contribute to the training of qualified and productive scientists, engineers and technical staff. People trained in this process are expected to take part in the works carried out within the framework of Turkey's "National Technology Move".

We believe that, it is important to improve the infrastructure of schools in order to use 3D printing technology effectively and efficiently in education and training in today's world. In this context, it is necessary to include relevant technical courses in the curriculum, to have qualified technical staff, and to have sufficient application areas (workshop, laboratory, etc.). Administrators of public and private schools should work in cooperation with parent-teacher associations on this issue. It is important that such production technologies and systems of the age are included in the curriculum and implemented in an efficient manner. In particular, it can make an important contribution to the establishment of a robust industrial revolution which gained momentum in recent years in the field of education.

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