**Soya chunks-bamboo toothpick molecular model: An Eco-friendly model for Chemistry teaching in resource-limited settings**

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**Abstract**

Physical and computer models are frequently used at all levels of science teaching. In emergency and resource limited environments an affordable, easy to implement, and environmentally friendly model would be important for effective teaching. Here, we report on a homemade ball-and-stick type molecular model made from soya chunks and bamboo toothpicks. We implemented the model for high school and graduate level Chemistry teaching both in online and classroom environments. The end semester survey (n=206) showed the model is easy to use and made learning easier. Our study suggested that the model can be an effective and ecofriendly alternative to teach some of the *difficult-to-understand* topics in Chemistry and related disciplines in resource limited settings.

*Keywords*: COVID‒19; Online teaching; Homemade molecular models

**1. Introduction**

In science a model is thought as an important component to bridge abstract theory and the experiment. Scientific community use models to simplify abstract concepts and to develop new theories(Gilbert, 1998; Passmore et al., 2014; Treagust et al., 2002). A good model stimulates creative thinking and increases learner's interest. The use of molecular models to understand different phenomena in teaching Chemistry and related discipline is in practice since long time(Peterson, 1970). In Chemistry, effective teaching of certain topics such as molecular geometry and symmetry, hybridization and bonding, and isomerism the understanding of spatial organization of atoms in three dimensions is important. This is possible from the use of proper molecular models. The physical and computerized molecular models are in common practice in Chemistry teaching and learning(Barnea & Dori, 1996; Dori & Barak, 2001). An instructor molecular model should be easy to assemble and manipulate, should work for simple to complex molecules, and the size suitable for classroom demonstrations.

The ball and stick type molecular models are most commonly used physical models. In these models spheres of different size and colors represent atoms in a molecule. The atoms are connected by rods or sticks which represent the bonds. The commercially available models are mostly made from plastic materials and are not environmentally friendly. They are either costly or not easily available in resource limited settings. To overcome these limitations, homemade or Do It Yourself (DIY) type molecular models made from locally available materials are being explored in literature; for examples lecture size models for orbitals made from plastic soda bottles(Samoshin, 1998) and whiteboard markers(Dragojlovic, 2015), screw on bottle caps models(Siod\lak, 2013), styrofoam models for *d* orbitals(Saieed, 1980), models made from poodles to illustrate chirality at two centers(Feldman, 1984; Nave, 1991).

In recent years due to advent of 3D printer and software, 3D printed models are also being explored for teaching(Blauch & Carroll, 2014; Gallardo-Williams et al., 2020; Paukstelis, 2018; Rossi et al., 2015; Van Wieren et al., 2017). The 3D printing method is scalable and, with a proper software, models of simple to complicated molecules can be constructed. On the other hands, computerized modeling software(Barnea, 2000; Barnea & Dori, 1996), simulation based learning(Schwedler & Kaldewey, 2020), augmented reality techniques(Abbasi et al., 2017) are also used in Chemistry teaching. However, the requirement of 3D printers and or computers, fast internet, and specific software limits the use of these methods in resource limited settings.

In pandemics, including the ongoing COVID-19, online teaching is practiced in all levels of teaching and in all parts of the globe(Basilaia & Kvavadze, 2020; Fung & Lam, 2020; Mian & Khan, 2020; Okebukola et al., 2020; Soares et al., 2020; Tan et al., 2020). Certain Chemistry topics such as, molecular geometry and symmetry, hybridization, bonding are very difficult to teach without the application of physical molecular models. In resource limited environments, commonly used ball and stick type physical models are not easily available. Also, such models are mostly made from plastics and are not environmentally friendly. A molecular model that is cheap, easy to assemble, flexible, and can be implemented for both online and class room teaching in resource limited settings would be important.

In this work, we developed a cheap and easy to assemble molecular model using soya chunks and bamboo toothpicks. We implemented the model to teach: a) molecular geometry and chemical bonding for 12th graders in online platform during COVID-19, and b) molecular geometry, symmetry elements and operation for Graduate level in both online and classroom settings. We also made a survey study to get students' perspective on the effectiveness of the model in teaching and learning. Finally, a discussion on advantages and possible limitations of the model is provided.

**2. Methodology**

***2.1 Materials***

The proposed molecular models was constructed using soya chunks, bamboo toothpicks, and white board markers. These materials were purchased from the local retail market at rate of $1/kg (soya chunks), $0.5/200 piece (toothpicks), and $0.3/per piece (board marker); respectively. The soya chunks had almost spherical size with diameter ~1.5 cm and the toothpicks had pointed ends with length of around 7 cm. For long term storage, the materials were stored in a dry and closed plastic container. A photograph of the accessories required in this method is provided in figure 1.



**Figure 1:** Accessories required to make the molecular models. A) Soya chunks, B) Bamboo toothpicks, and C) white board markers.

***2.2 Model construction***

To make the molecular models, soya chunks and bamboo toothpicks were used to represent atoms and bonds, respectively. The physical models of different molecules were made by connecting soya chunks with toothpicks. For stable connection the toothpicks should inserted ~1/3 of the soya chunks diameter. Single, double, and triple toothpicks were used between two soya chunks to represent single, double, and triple bonds, respectively. To distinguish the atoms and bonds of different types, the soya surface can be colored black, blue and red with white board markers. A lone pairs of electrons were represented by putting two white board marker ink dots on the soya surface.

***2.3 Implementation of the model in online and classroom teaching***

The model was used to teach molecular geometry and chemical bonding topics for 12th graders during the COVID-19 lockdown. The Microsoft team platform used for online teaching. The model was used in three online classes each having ~45 students. Different concepts related to molecular geometry and bonding such as bond order, bond type, lone and bond pairs, and three dimensional arrangement of atoms in different molecules such as acetylene, ethylene, methane, benzene were explained and demonstrated using the model. During and after the class, students were encouraged to build models of different molecules. An online survey using Google survey platform was conducted to get students' perspective on the molecular model. The survey questionnaire was reviewed and approved by the Head of the Institution. Personal information of the students was not collected to minimize the student bias in the survey. The responses were downloaded and analyzed in excel.

The model was also implemented to teach symmetry elements and operations in three Graduate Chemistry classes; an online class of 90 students during COVID lockdown (March-July 2020) and two offline (onsite) classes each having 45 students (February-July 2019). In the classes, students were to make three dimensional structures of different molecules such as hydrogen peroxide; boron trifloride; xenon-tetra, -penta, and -hexa floride; and diborane. The model was used throughout the semester to explain the different concepts related to molecular geometry and symmetry elements and operations such as molecular geometry, planar versus non planar molecules, axis of rotation and rotational symmetry operations, planes of symmetry or mirror planes and operations, conformers, center of inversion or inversion center and its operation, and symmetry transformations using physical models of different molecules. Students were encouraged to make their own models during the class hours and at home to understand the lecture notes and solve homework. At the end of the semester, a short survey was conducted to get an overall perspective of the students on the method of teaching. The survey questionnaire was reviewed and approved by the Head of the institution. The questionnaire in provided in the supporting information (S2B).

**3. Results**

***3.1 Construction of the model***

The three dimensional structure of some of the molecules constructed and discussed during online and offline teaching hours is shown in figure 2A‒G. The soya chunk surface can be easily pricked with tooth picks in all directions. Also, single, double, and triple bonds can be made by putting one, two, and three toothpicks between a pair of soya chunks respectively. Because of these flexibilities, molecules having diverse geometry and bond multiplicity can be easily constructed. Some of the notable features in the model structures (Fig 2A-G) are: 1) lone pairs of electrons in each oxygen atom of H2O2 represented by putting two pair of dots with a black marker, 2) triple bonds in acetylene represented by putting three toothpicks between a pair of carbon atoms, 3) equatorial and axial bonds in XeF5 and XeF6 with the central Xe atom coded black, 4) the three centered two electron or bridging B-H-B bonds in diborane with boron atoms coded red.



**Figure 2:** Physical models of different molecules. A) Linear hydrogen peroxide (H2O2); the lone pair of electrons in oxygen atoms are indicated by black dots. B) Acetylene (C2H2); triple bonds are represented by three toothpicks between a pair of carbon atoms. C) Boron trifloride (BF3); florine atoms labeled as F1, F2, and F3. D) Xenon tetrafloride (XeF4). E) Xenon pentafloride (XeF5). F) Xenon hexafluoride (XeF6). G) Diborane (B2H6). For clarity, central atoms are coded in different colors using board markers.

The proposed method provides excellent connection and rotational flexibilities so that isomers of a molecule can be easily constructed. The method was also used to demonstrate the conformational isomers of different molecules during the class hours in both online and offline graduate classes. As an example, the eclipsed and staggered conformations of ethane is shown in figure 3A and B, respectively. The front and back ‒CH3 units are nicely depicted in the model of eclipsed ethane. Since the model provides excellent rotational flexibility, one conformer can be converted to other by rotating (60o clock or anti‒clock wise) front or back ‒CH3 units along the C‒C single bond.



**Figure 3:** Conformational isomers of ethane. A) Eclipsed ethane. B) Staggered ethane. Carbon are coded black.

The model was also used to demonstrate symmetry elements (axis of rotation, symmetry plane, inversion center) and operation in different molecules both in online and offline Graduate classes. Some of the examples that were demonstrated and discussed in the class are provided below.

* This method was used to show C3 (three fold rotation axis i.e. an out of plane rotation by 120o) symmetry operation in a triangular planar molecule. It is very easy to show that C3 operation three times is equal to identity operation E i.e. C33=E (see figure 4A). In the model, the direction of C3‒that lies perpendicular to the plane of BF3‒ is shown by a toothpick pointing vertically upward from the molecular plane
* BF3 contains three vertical planes (σvi, i=1, 2, 3) that lie along each B-F bond and bisect the other F-B-F angle. The σv1 lies along the B-F1 bond and bisects F2-B-F3 bond angle is shown in figure 4B. The σv1 operation swaps the position of F1 and F2 (figure 4B). Similarly, other vertical planes (σv2 andσv3) and their operation can be easily depicted.
* In the next example, the model was used to show inversion operation in a square planar molecule. Inversion operation swaps the coordinates of an atom from (x, y, z) to (-x, -y, -z). The inversion on XeF4, swaps the position of atoms 1 and 3 and 2 and 4; as depicted in figure 4C. Again, we can easily show that inversion operation two times (i2) is equal to identity E i.e. i2=E.



**Figure 4:** Demonstration of molecular symmetry and operation in different molecules. A) C3 rotational symmetry element and its operation in BF3. The florine atoms are labeled 1, 2 and 3 to follow their position change in successive C3 rotation (120o rotation clockwise). B) One of the vertical planes and its operation in BF3. The vertical plane (σv1), depicted by a piece of paper lying vertically to the molecular plane, swaps the position of florine atom 2 (F2) and 3 (F3). C) Inversion center (labeled i) and its operation in XeF4. As expected, the inversion swaps the position of florine atom 1 and 3 and 2 and 4.

These examples demonstrated that the model is very flexible to teach and understand symmetry elements and operation in different molecules.

***3.2 Survey study***

At the end of class, a survey was conducted in three high school chemistry classes (12th graders). The survey was intended to get students' perspective on the teaching method and effectiveness and flexibility of the model. The survey results are provided in figure 5A and B.



**Figure 5:** Survey study on theeffectiveness of the model in 12th grade online Chemistry class. (A) Student response on the overall effectiveness and preference of the model, (B) response on the ease of use and flexibility of the model. The total responses obtained from three online classes was 114 (n=114).

Survey was also conducted in both online and offline Graduate chemistry classes. The results are provided in figure 6A and B.



**Figure 6:** Survey study on theeffectiveness of the model in graduate chemistry class. A) Online teaching (n=50), and B) classroom teaching (n=42).

**4. Discussion**

***4.1 Students' feedback obtained from 12th graders***

In the survey, students were asked to provide their feedback on the effectiveness of the model in understanding the concepts on molecular geometry and bonding. Out of total respondents (n=114), ~48% (55/114) agreed that the model is very effective, ~49% (56/114) responded that the model is effective, and only ~2.5% (3/114) responded that the model is not effective (figure 5A). Interestingly, ~98% responded that they used or planning to use the model to make models of different molecules and ~97% prefer to use the model to better understand other relevant topics in Chemistry (Figure 5A). This results suggested that the model makes teaching and learning effective in online teaching platform.

Students were also asked to rate the molecular model in terms of flexibility and user convenience in the scale of 1 to 10; 1 and 10 implied lowest and highest rating, respectively. Interestingly, the model was rated high (≥7) by ~82% respondents, medium rated (rating of 5 and 6) by 14% respondents, and low rated only by ~3% respondents (Figure 5B). These data suggested that student find the model is flexible and convenient to use.

Finally, students were encouraged to provide overall impression on the molecular model in written form. Almost all respondents (~97%) provided very positive feedback. Few representative responses made by the students (with typos corrected in the text) are provided below.

*Student 1: "I find your way of teaching quite easy. I wish we had such guidance in grade 11 too. This way of using homemade molecular model is very interesting and easily understandable comparatively with the slide or board teaching."*

*Student 2: "Yes it is effective for me to learn to understand geometry of different molecules in a 3d vision. Otherwise in board or in book I used to find only 2d picture. In coming days I will also apply this method to teach my junior and to present geometry of molecules in a 3d vision."*

*Student 3: "Previously our teacher tried to explain the model through a marker & a whiteboard, let's be honest that was really hard to understand. The 'soyabean' model idea blew my mind & only today I've understood the tetrahedral shape or model. This model is also really cheap & easy to make. In short, I found this model to be really interesting & effective."*

*Student 4: "The idea to use household materials for chemistry and understanding the structures of molecules in a modern way is quiet fun and not that complicated to handle. Buying these structures don't take time but we may not go after it every time and probably not remember the geometry of those molecules. But when we practically make them on our own or with the help of teachers' guidance, it would make classes even more interactive and we get to visualize those structures."*

*Student 5: "Easy to make and effective to understand."*

*Student 6: "It is very helpful for students. It is flexible and less expensive."*

*Student 7: "It helps in understanding about the models clearly. It may takes our time but will help in learning in new methods new topics and so on. It is good to understand the structures of molecules. New method new way to us brings eager and curiosity to learn and make it."*

The above written statements suggest that students enjoyed teaching and learning. They found the model flexible and convenient. Some of the students mentioned that they used the model for the first time and prefer to use the model to understand other chemistry topics. They also believed that the model provides a low cost, accessible, and environmentally friendly alternative.

***4.2 Students' feedback obtained from graduate class***

In the online teaching 70% (35 out of 50, 30% (15 out of 50) and 0% students responded that the model was highly effective, effective and not at all effective to understand the geometry different molecules; respectively (Fig. 6A). Similarly, in the classroom teaching ~55% (23 out of 42), ~40 % (17 out of 42), and ~5% (2 out of 42) students responded that the model was very effective, effective and not at all effective; respectively (Fig. 6B).

Students also made strongly positive response on the effectiveness of the model to understand the concept of symmetry elements and operation both in online and offline teaching. Additionally, ~62% of classroom students and 100% of the online students agreed that they used the model at home to revise the lecture notes. Also, 90% of the respondents in the online teaching mentioned that the model was even used to solve homework problems (homework was not included in classroom teaching). These observations suggested that: i) the use of model made learning easier, and ii) the model is even more effective in online teaching platform.

In the survey, student were also requested to make a short remarks on the overall use and effectiveness of the homemade molecular model (please find the last question of the survey in supporting information). The comment was made only by 39 (out of 50 participants) and 26 students (out of 42 participants) in the online and offline teaching classes, respectively. Majority comments (~97%) were very positive and highlighted the importance of the model in understanding the molecular symmetry and geometry. Few representative responses made by the students are provided below.

*Student 1: "These models prioritize on efficient practical teaching methodology to understand the core geometrical configuration, and has made easier to visualize in 3D aspects. Thank you sir for your innovative approach that utilizes cheaper homemade materials to understand molecular symmetry."*

*Student 2: "I founded the homemade molecular model very much effective. It helped me to understand clearly the symmetry elements portion, how we can rotate elements through various angles and also helped me to understand about planner molecules, inversion symmetry etc. So homemade model was very effective for me. Thank you so much sir for teaching us by showing various molecular models."*

*Student 3: "Understanding the molecular geometry, only by imagination, in 3 dimensional pattern is a difficult task. So the use of homemade molecular models is the best option for this purpose. By using such a model, we can easily learn about the concept of symmetry elements and operation."*

*Student 4: "The 3D models helped a lot to understand the course content (3D symmetry and symmetry operations) which would otherwise be too hard to visualize mentally."*

*Student 5: "Find the use of bamboo tooth picks and soya chucks very effective techniques in understanding the geometry, symmetry group theory of various compounds."*

*Student 6: "Besides theoretical explanation, making molecular models practically was very helpful to understand about symmetry elements and operation especially on horizontal and vertical plane with respect to principal axis and to designate its principal axis."*

As in responses obtained from the 12th graders, students enjoyed teaching and learning and the model indeed helped to understand the 3D structure of molecules better.

***4.3 Advantages and limitations of the model***

The model offers following advantages.

* The physical size of the molecular model is determined by the length of bamboo toothpicks. Using toothpicks of ~7 cm long one can get the model size that works best for medium sized classroom (~45 students). Also, with the laptop screen slightly tilted forward the model can be used in online teaching platform.
* The major advantage of this method is the access it provides to models of unlimited number of molecules form simple planar to high symmetry molecules so that it can be easily implemented at every level of Chemistry teaching both online and offline.
* As compared to the commonly available plastic based ball and stick type molecular model, the materials used in this method are easily available and environmentally friendly.
* The model is very light, easy to carry, and affordable.
* If stored in dry container, the model can be used multiple times.
* The model provides excellent connection flexibility and easy to build. So, even after the lecture class, students can easily assemble these models to revise lecture notes and do homework.

These advantages suggest that that the method implemented here can be an easy to use, affordable, and environmentally friendly method to made models of different molecules. The model can implanted in all levels of teaching in both online and classroom teaching.

The model has following limitations.

* The physical size of the model is determined by the diameter of soya chunks and length of toothpicks. Although, size can be tuned by changing the size of materials, the model is less effective for large size class room.
* If the materials are not stored in a dry closed container, environmental damage can shorten the lifetime of the materials and the model.
* Care should be taken while pricking the soya surface with the toothpicks.

**5. Conclusions**

To summarize, we developed a method to construct molecular model using easily available materials. The model can be used to construct physical models of range of molecules from simple planar to high symmetry molecules. The model was implemented to teach range of chemistry topics such as molecular geometry, nature of bonding, symmetry elements and operation both in online and classroom settings at all levels of teaching. The end semester survey showed that the model indeed made teaching and learning easier. In the survey students also responded that the model is easy to use, flexible, and provides an affordable and environmentally friendly alternative. This study showed that the soya chunks‒bamboo toothpicks model can be affordable alternative to difficult‒to‒understand topics in Chemistry and related disciplines in resource limited settings.

**Conflicts of interest**

The authors have no relevant financial or non-financial interests to disclose.

**Data availability statement**

The data that supports the findings of this study are available in the main texts and the supplementary material of this article.

**Ethical statement**

All procedures performed in studies were in accordance with the ethical standards of the institution. The survey questionnaire was reviewed and approved by the Head of the institution.

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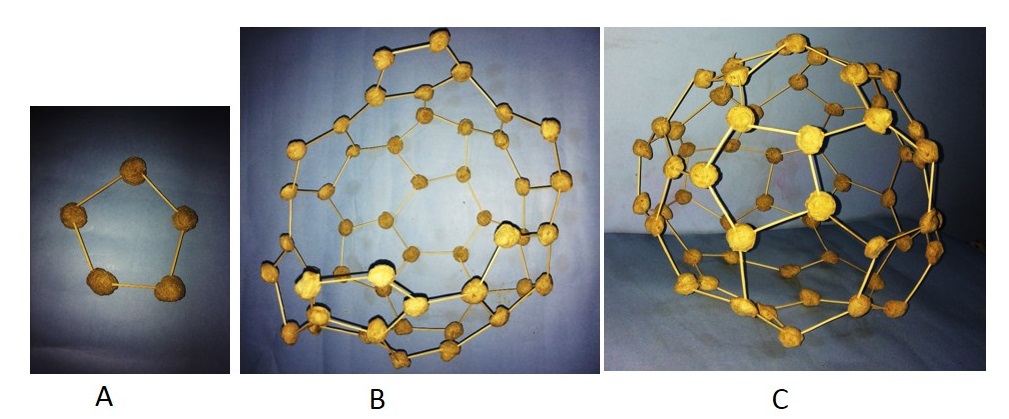
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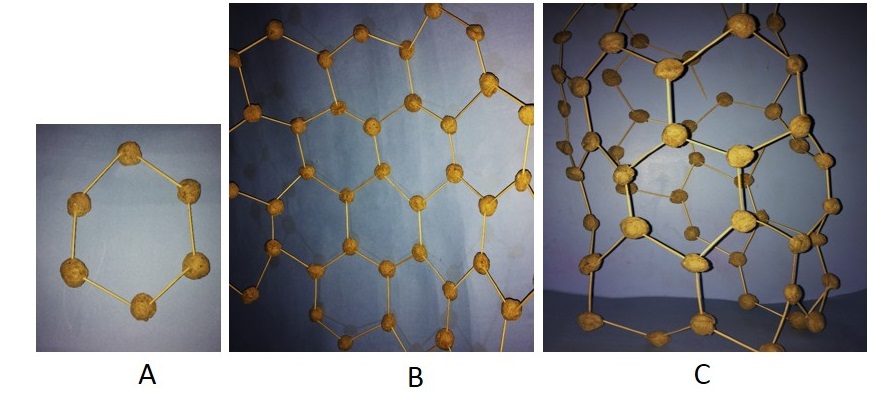
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*Supporting Information for*

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**Supporting figure 1***:* Different steps on the construction of C60. A) Pentagon; the building block, B) intermediate structure, C) final structure of C60.



**Supporting figure 2:** Different steps on the construction of model of single walled carbon nanotube. A) hexagon, the building block; B) intermediate structure, graphene sheet, and C) final structure, carbon nanotube.

**S2: Survey Questionnaire**

***S2A. Effectiveness of home built molecular models to understand the geometry of different molecules***

Dear students, I used Soya chunks-bamboo toothpick molecular model to teach the geometry of different molecules in the online class. I am conducting this survey, to get your feedback on the effectiveness of the homemade model in understanding the three dimensional arrangement of atoms in the molecules. I have developed few questions to get your overall impression on the mode. I highly appreciate your participation in a short survey. Your information will be kept confidential.

1. How effective did you find the model to understand the geometry of different molecules in the online class? \*

* Very effective
* Effective
* Not effective at all

2. Did you use or planning to use this model to make the shape of different molecules?

* Yes
* No
* others

3. Will you prefer to use this model to understand the shape of different molecules in other chemistry topics (for example organic chemistry lectures)?

* Yes
* No

4. How handy or flexible did you find this model to make the shape of different molecules?Rate in the scale of 1 to 10. [1=lowest rating, 10= highest rating]

5. Please provide your overall impression (both good and bad) regarding the homemade molecular model.

***S2B. Effectiveness of home built molecular models graduate chemistry teaching***

Dear students, our department is running online classes due to COVID-19 lock down. This semester, department had assigned me to teach molecular geometry, symmetry elements and group theory. You all know, I was using a home built bamboo toothpicks- soya chunks molecular models to teach these topics. I am conducting this survey, to get information on effectiveness of the models that I used in the online teaching. I have developed few questions to get your input. Your information will be kept confidential.

\* Required

1. How effective did you find the model to understand the geometry of different molecules in the online class? \*

* Very effective
* Effective
* Not effective at all

2. How effective did you find the model to understand the concepts of symmetry elements in the online class? \*

* Very effective
* Effective
* Not effective at all

3. Did you make molecules having different geometry using the bamboo toothpicks and soya chunks at home? \*

* Yes
* No

4. Did you use the model at home to understand/revise the lecture notes on symmetry elements and operation? \*

* Yes
* No

5. Did you use or planning to use this model to solve homework problems? \*

* Yes
* No

6. Please make overall comments on the homemade molecular model and its effectiveness