

# Research on the application of nanocomposite materials in children's physical exercise equipment

Huanxiang Ding<sup>1</sup>, Xueqin Wang<sup>1</sup> and Xiaodao Chen<sup>\*2</sup>

<sup>1</sup>College of Physical Education and Health, Linyi University, Linyi 276005, Shandong, China

<sup>2</sup>Department of Physical Education, Guangdong University of Finance, Guangzhou 510521, Guangdong, China

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**Abstract.** Combating the worldwide environmental threat of plastic waste pollution has become a priority. Plastic pollution has the potential to impact land, rivers, and seas, since many marine and terrestrial organisms have perished as a result of plastic's non-biodegradability and soil dangers. For this consumption, it seems required to manufacture and use new renewable resources. Renewable materials for diverse applications have been created utilizing nanotechnology, which may replace conventional materials for children's activities and sports equipment. This study investigates and suggests that nanotechnology-based materials be replaced with conventional materials to save the environment in manufacturing equipment for children's physical activities. On the basis of the mechanical sciences, a stability study of the bending behavior of small-scale structures will be performed for the various recommended materials.

**Keywords:** bending analysis; nanocomposite materials; nanotechnology; renewable materials; sport equipment

## 1. Introduction

Small-scale structures and materials are a very appealing choice for designers to employ to manufacture more efficient devices with higher durability, as micro and nanotechnology offer new designs that enhance the structures' preferred properties (Raja *et al.* 2004). Small-scale technology can increase the stiffness of the structures, lower the weight, increase the durability, and make the structure less prone to fracture, making it ideal for the devices used for the structures that are utilized by children.

Nowadays, the population of overweighted children is rising over the world. Being overweight in the early stages of life can cause various health problems, such as diabetes and cardiovascular problems (Singh *et al.* 2008). It has been shown that there is a direct relationship between low physical activities and overweighted children (Rennie *et al.* 2005). Thus, it is essential to encourage children to do physical activities. With this in mind, there are various types of equipment by which children can perform their physical activities (Maher *et al.* 2008). Children can use various indoor and outdoor facilities, such as climbing structures, jumping equipment, slides, balancing surfaces, merry-go-rounds, and see-saws (Gubbels *et al.* 2012).

With the aid of small-scale technologies, scientists have reached a better and more efficient design for various devices with more durability (Naderi *et al.* 2021). Plastic is one of the most utilized materials in children's toys and exercise equipment. Plastic materials are not only not as strong as the new types of nanocomposites but also toxic to nature (Xu *et al.* 2021b). There has been much effort

devoted to finding a replacement for such materials. Nanocellulose is one of the nano-based composites which can be built from biological wastes (Shreedhana and Ilavarasi 2020). These materials are quite strong and resistant to fracture. Additionally, nanocellulose is nature-friendly and can be degraded in nature. Also, toys made of such materials, unlike plastics, are not toxic to children (Mann *et al.* 2018).

It has been shown that the nano- and micro-structures mechanical characteristics can be altered as the structure's size is changed. Therefore, it is vital to investigate various size-dependent factors related to these structures (Fakher *et al.* 2020). In this regard, different papers studied small-size systems' vibration (Naderi *et al.* 2020), buckling (Aydogdu 2009), bending (Malikan and Eremeyev 2020), and stability (Baghani *et al.* 2016). The stability margin is considered the functional region in which the device can be implemented. With this in mind, the stability analysis associated with small-scale structures such as beams (Karličić *et al.* 2018), wires (Guo *et al.* 2016), and plates (Kolahchi *et al.* 2016) is explored. For example, Tsai and Chen (2002) investigated the dynamic stability associated with a wire made of memory alloy composite. They utilized harmonic balance along with the finite element method to extract their results. Also, the vibrational behavior as well as dynamic and static stability of beams made of FG materials were studied with the help of GDQM as the numerical solution (Chen *et al.* 2019). The stability analysis related to FG microbeams was presented by implementing Timoshenko and modified couple stress theories (Ke and Wang 2011). In the mentioned article, the results were obtained by using the DQ method. In addition, Fu *et al.* (2009) carried out a paper on the nonlinear dynamic stability of microbeams made of viscoelastic materials based on Galerkin method and Euler-Bernoulli. According to isogeometric procedure, the

\*Corresponding author, Ph.D.,  
E-mail: 30-007@gduf.edu.cn

dynamic stability of plates whose constitutive material is porous media was investigated (Pham and Nguyen 2022). On basis of HSDT and MCST, the stability formulation related to three-layered plates made of reinforced composites was attained and solved via DQM (Emdadi and Mohammadimehr 2021). The stability investigation on the laminated composite disks was done through MCST and GDQM (Al-Furjan *et al.* 2021). The plate was assumed to be resting on a viscoelastic medium.

There are different theories by which the small-scale structures can be mathematically formulated to investigate the structure's size-dependent behavior. Two-phase theory (Naderi *et al.* 2022), nonlocal elasticity (Eringen and Edelen 1972), and modified couple stress (Park and Gao 2006) are among the most implemented hypothesis (Bai *et al.* 2021, Hu *et al.* 2021, Ning *et al.* 2021, Sheng *et al.* 2021, Han *et al.* 2022, Zhang *et al.* 2022b, Zhou *et al.* 2022). Regarding this, Asghari *et al.* (2010), by utilizing Timoshenko together with modified couple stress theories, presented the nonlinear formulation associated with microbeams with simply supported end conditions. Also, the nonlinear dynamic behavior of microbeams was explored via the Galerkin method and MCST (Ghayesh *et al.* 2013). Next, it can refer to the work by Park and Gao (2008) in which the variational formulation and implementation of MCST is presented.

Plastics are the primary fundamental material for producing children's physical exercise equipment, however, they are hazardous to the environment, so the alternative materials that are harmless to the environment should be replaced. Wood is a good alternative, but they are limited, and its reproduction is timely and high-cost. In this regard, the current paper investigates the impact of using various types of materials such as plastic, wood, nanocellulose, and nanocomposites on the static bending of wires. The formulations of small-scale wire are obtained by means of the energy method as well as modified couple stress theory. The results are extracted via the Navier solution procedure. The results are validated by comparing them to those from other published data. The influence of factors such as small-scale parameters and geometrical characteristics on the mid-displacement of wires is explored.

## 2. Description of problem

### 2.1 Physical activities and exercise

Physical activity refers to a wide range of movements, particularly major skeletal muscles. Small skeletal muscle activities (e.g., playing board games, sketching, writing) are necessary for the body, however, these activities do not have as many advantages as extensive activities which require much energy.

Physical activity is classified according to its duration, intensity, and frequency:

- The duration of a physical exercise session is the amount of time spent engaging in it.
- The energy expenditure rate is defined as intensity.
- The amount of physical activity sessions over a certain

time period is referred to as frequency (e.g., one week).

Exercise consists of planned and organized activities that maintain or develop one or more components of physical fitness. "physical activity" and "exercise" are sometimes utilized interchangeably. "Physical activity," on the other hand, refers to a broad range of activities that enhance well-being and health, while "exercise" is connected with maintenance of fitness or developing it. To accomplish certain fitness and performance objectives, people must concentrate on the frequency, intensity, and length of exercise sessions.

Physical activity programs assist to prepare children and adolescents for a lifetime of physical exercise. The manner in which health professionals deliver physical activity programs to children and adolescents may have a substantial impact on their degree of physical activity involvement. As a result, it is critical for health professionals who care for children and adolescents to understand the fundamentals of physical education programs.

Physical exercise is classified into two types: lifestyle and structured (or systematic). Walking, climbing stairs, performing chores, and playing are examples of lifestyle physical exercise. Structured physical activity refers to programs (for example, sports and instructional programs in dancing, gymnastics, and swimming) that aim to improve the quality and/or intensity of physical exercise. Structured physical exercise aids in the development of muscular strength and endurance, flexibility, and cardiovascular fitness in children and adolescents, as well as the attainment and maintenance of a healthy weight.

Structured physical activity programs are classified into two types:

- Physical education programs during the school day
- physical activities done at school or in non-school places.

There are guidelines available for analyzing and developing school and community initiatives to encourage physical exercise for children and adolescents. Policy, health education, the environment, physical education, parental participation, staff training, health services, community programs, extracurricular activities, and program assessment are all addressed in these standards.

### 2.2 Materials used for children's physical exercise equipment

There are several rules in place across the globe to regulate and control the use of hazardous additives and possibly deadly substances in plastic toys. Chemicals in toys and childcare items, for example, are controlled in Europe by the Toy Safety Directive 2009/48/EC, which restricts or prohibits the use of more than 70 compounds (e.g., phthalates, allergenic fragrances, reducing agents). Phthalates plasticizers are controlled in North America under the Consumer Product Safety Act in Canada and the Consumer Product Safety Improvement Act (CPSIA) in the United States. Similarly, phthalate additive rules are in place in certain other nations, including Japan and Egypt. However, there is a lack of a uniform worldwide strategy to

regulate chemicals in children's goods and toys internationally. Existing restrictions often concentrate on specific chemicals (e.g., phthalates, brominated flame retardants, and metals), rather than the whole variety of chemical compounds contained in plastic toys. Furthermore, certain harmful and prohibited compounds are still discovered in plastic toys on controlled markets, for example, due to recycling harmful plastics, manufacturer ignorance, or a lack of restrictions in the manufacturing nation. Throughout this work, "toy materials" connected to any type of material, plastic as well as non-plastic, while "plastic toy materials" are plastic polymer matrices (Aurisano *et al.* 2021).

Chemical risk screening methodologies created for alternative evaluation and chemical replacement are a good place to start when comparing the numerous chemicals in plastic toys for possible exposure and danger. Existing technologies, however, lack effective ways for quantifying exposure for the hundreds of commercially available chemical-material combinations. High-throughput screening technologies might be used instead to quantify exposure to toxins in different toy materials (Aurisano *et al.* 2021).

### 2.3 The alternative material for the child's toys and physical exercise equipment

Nanomaterials, due to their optical features, uniformity, and conductivity are an exciting choice for scholars to investigate. Researchers in different fields such as physics, biology, mechanics, and chemistry are studying the application of these structures, which cannot be seen without an electron microscope. These materials are between bulk and molecular materials, showing extensive features.

Nanomaterials are broadly utilized in plastics, paints, ceramics, etc., which makes them a source of pollution on the Earth. They are produced via meteorological, cosmological, and geological processes.

Nanomaterials, which are materials including one particle on nanoscale, can be produced through industrially engineering, natural processes, and a byproduct of other processes. Currently, there are various investigations on the nanoscale material and structures are being done to understand and find the usage of these materials. It has been shown that these materials can be employed in the electrical, cosmetic, healthcare, and sports industries. With this in mind, one of the newest implementations of these materials is controlling the land, air, and water pollution.

Nanomaterials can be employed to confront pollution in various ways, one of which is using these materials as the catalyst to absorb pollutants such as carbon dioxide. Another thing that nanotechnology can help us with is that the sensors manufactured on a nano-scale can detect toxic materials with higher precisions. Also, these materials can absorb pollutants and turn them into usable materials such as alcohol (Habibi *et al.* 2016, 2018b, Ebrahimi *et al.* 2019a, Esmailpoor Hajilak *et al.* 2019).

In addition, nanomaterials are able to absorb the dye, which is the byproduct of the leather and textile industries. These toxic materials can harm the human body as well as animals and plants. Nanomaterials help to absorb the toxic

materials together with the oils which are released in the water (Habibi *et al.* 2018a, 2019b, d, e, Pourjabari *et al.* 2019, Safarpour *et al.* 2019a).

Also, nanomaterials are able to digest organic wastes, whose degradations are usually too slow. These materials can be digested much faster with the aid of nanomaterials (Habibi *et al.* 2019a, Safarpour *et al.* 2019b, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Chen *et al.* 2022).

Nanocellulose is one of the nanomaterials which can be utilized instead of common plastic. Nanocellulose, extracted from the carbohydrates of wood or cotton, is one of the most abundant substances on Earth. These materials are strong, lightweight, able to conduct electricity, and transparent. Also, they can reduce the usage of fossil oils to produce toxic plastics. They can replace plastic in food packages and protective layers (Habibi *et al.* 2017, 2019c, Safarpour *et al.* 2018, 2020, Ghazanfari *et al.* 2020). Additionally, nanocellulose is implemented for building flexible screens, medical implants, and repairing damaged tissue in the body (Ebrahimi *et al.* 2019b, c, 2020b, Mohammadi *et al.* 2019, Mohammadgholiha *et al.* 2019, Habibi *et al.* 2020, Shariati *et al.* 2020a, Shokrgozar *et al.* 2020).

Plastic is cheap, easy to shape, and strong in production, however, plastic trash is a quickly developing environmental problem. Around 40% of wasted plastic is from packaging. Thus, there is a need to make a replacement for the plastics which have the durability and ability to be degraded in nature. Regarding this, the paper can be a good choice as they are adaptable and can be recycled. However, they are not as robust as Nanocellulose is. Nanocellulose causes no harm even if it is eaten (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, 2020b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020b).

The wood fiber, extracted from wood, can be utilized to make cellulose fibers via chemical process. With the aid of the cellulose molecule's bundle, the nanocellulose can be joined together and make a firm bond. Also, the nanocellulose can help with extracting the oil as it can alter the viscosity of water when it is added to water (Hashemi *et al.* 2019, Al-Furjan *et al.* 2020e, Cheshmeh *et al.* 2020, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020c).

Nanocelluloses are non-toxic, can be degraded in nature, are very strong, and can transmit electricity. These materials can be produced in a quite small scales, nano or micro (Al-Furjan *et al.* 2020c, d, f, Bai *et al.* 2020, Li *et al.* 2020a, Zhang *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021a).

In high quantities, they are produced cost-effectively. When used as a basis for foams and aerogels, nanocellulose is highly absorbent. It is the Earth's most abundant polymer. Additionally, nanocellulose can be produced with a reasonable price. Thus, nanocellulose, due to its remarkable features such as lightweight and extraordinary strength, can be employed in various parts of engineering devices, medical devices, packaging, oil industries, and even toys for children (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b).

### 2.4 Mechanical simulation and stability analysis

This section presents the stability analysis regarding the

bending behavior of the small-scale structures of both plastic, wood, and nano-cellulose (Li *et al.* 2021, Si *et al.* 2021, Zhang *et al.* 2021a, Wang *et al.* 2022c). Accordingly, a wire structure made of both mentioned materials is assumed based on the Euler-Bernoulli beam theory as well as the modified couple stress theory (Wang *et al.* 2022a, Zhang *et al.* 2022a, Cheng *et al.* 2023). Concerning these theories, the potential energy (P) will be presented as follows (Hou *et al.* 2021, Huang *et al.* 2021b, Xu *et al.* 2021a, Wang *et al.* 2022b):

$$2P = \iiint (m : \chi + \sigma : \varepsilon) dv \quad (1)$$

where ‘m’ is the deviatoric sections (Shafiei and She 2018, Shafiei *et al.* 2019, 2020). Additionally, ‘ $\chi$ ’ denote symmetric curvature equation related to small-scale theory. Also, ‘ $\sigma$ ’ and ‘ $\varepsilon$ ’ defined the stress and strain equations. They are defined as follows (Ebrahimi and Shafiei 2017, Ghadiri *et al.* 2017e, Mirjavadi *et al.* 2017a, Shafiei and Kazemi 2017a, Shafiei *et al.* 2017d, Azimi *et al.* 2018):

$$2\chi = \nabla\theta + (\nabla\theta)^T \quad (2a)$$

$$m = 2l^2\mu\chi \quad (2b)$$

In which Lamé constants are ‘ $\lambda$ ’ as well as ‘ $\mu$ ’. Also, ‘ $l$ ’ is the size-effect parameter of couple stress theory (Ehyaei *et al.* 2017, Ghadiri *et al.* 2017c, d, Mirjavadi *et al.* 2017d, Shafiei and Kazemi 2017b, Shafiei *et al.* 2017c).

$$\varepsilon = \partial u / \partial x - z \partial^2 w / \partial x^2 \quad (2c)$$

$$\sigma = E\varepsilon \quad (2d)$$

The virtual energy of external work (bending force,  $\eta$ ) is assumed as follows (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b):

$$\delta V = -\iiint \eta \delta(w) dv \quad (3)$$

Then, on the basis of the energy method, which is presented as follows (Ebrahimi and Shafiei 2016, Shafiei *et al.* 2016c, d, f, Ebrahimi *et al.* 2017, Shivanian *et al.* 2017):

$$\delta V + \delta P = 0 \quad (4)$$

The governing equation due to the bending response of small-scale wire is presented by substituting Eqs. (1) and (3) into Eq. (4).

$$l^2 Q_{10} \partial^4 w / \partial x^4 + Q_{22} \partial^4 w / \partial x^4 = -\eta \quad (5)$$

where

$$\begin{cases} Q_{10} \\ Q_{22} \end{cases} = \begin{cases} 0.5EA / (1+\nu) \\ EI \end{cases} \quad (6)$$

where ‘E’ is the elasticity modulus, ‘ $\nu$ ’ is the Poisson ratio, ‘I’ and ‘A’ are the second-moment area of the wire (Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al.* 2016a, e, g). Also, the boundary conditions are as follows Ghadiri and Shafiei 2016b, Ghadiri *et al.* 2016a, b, c, d,

Shafiei *et al.* 2016b):

$$\delta(w_{,x}) : (Q_{22} + Q_{10}l^2)w_{,xxx} = 0 \quad (7a)$$

$$\delta(w) : (Q_{10}l^2 + Q_{22})w_{,xxx} = 0 \quad (7b)$$

## 2.5 Solving procedure

The Navier solution is used for the problem, so the following assumption is necessary (Liu *et al.* 2020a, Wang *et al.* 2020, Zhou *et al.* 2020, Dai *et al.* 2021a, Guo *et al.* 2021a, Shao *et al.* 2021, Wu and Habibi 2021).

$$w = \sum_{q=1}^{\infty} W_q \sin(\pi x q / L) \quad (7)$$

where ‘w’ is the lateral displacement. Finally, the bending deflection will be obtained by substituting Eq. (8) into governing equation (Liu *et al.* 2020b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Liu *et al.* 2021b, Zhang *et al.* 2021).

$$w = \sum_{q=0}^{\infty} \frac{\mu}{\alpha} \sin(x \pi q / L) \quad (9)$$

where

$$\mu = \frac{2}{L} \int \eta \sin(x \pi q / L) dx \quad (10a)$$

$$\alpha = (l^2 Q_{10} + Q_{22})(p\pi / L)^4 \quad (10b)$$

## 3. Discussion of results

As explained in detail, plastics are the primary fundamental material for producing children’s physical exercise equipment, however, they are hazardous to the environment, so the alternative materials that are harmless to the environment should be replaced. Wood is a good alternative, but they are limited, and its reproduction is timely and high-cost. The nanocellulose can be a good choice, according to the previous explanation. As a result, in this section, the stability analysis of small-scale wire structures for plastic (Harper 2000), wood (Bodig and Jayne 1993), nanocellulose (Dufresne 2013) along with the nanocomposite materials (Srivastava and Kumar 2019) will be presented, and their results will be compared and investigated in detail. In which the mechanical properties of these materials are presented in Table 1.

In investigating the numerical examples, the validation of results are one of the major steps toward the study. To do so, Table 2 is presented in this article. In this Table, the mid-displacement associated with a wire are extracted and compared with various beam types. The close agreement between the deflection obtained through current formulations and those from other references indicates the validity and accuracy of the presented model.

Now, the impact of various parameters on the static

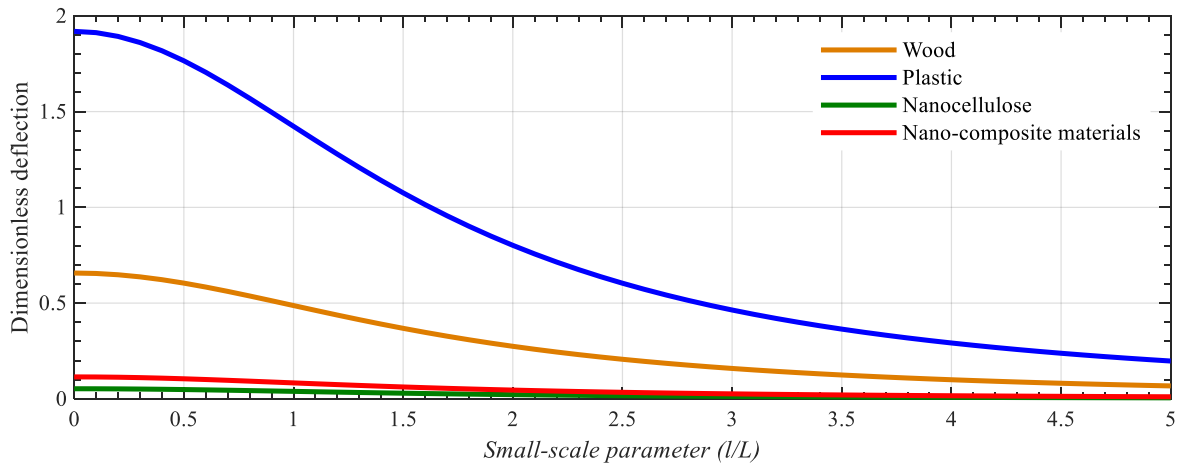


Fig. 1 Effect of the size-dependent parameter ( $l$ ) on the dimensionless center deflection ( $10\pi^2wE_{plastic}I/\eta L^3$ ) of small-scale wire versus the different materials,  $L/R=35$

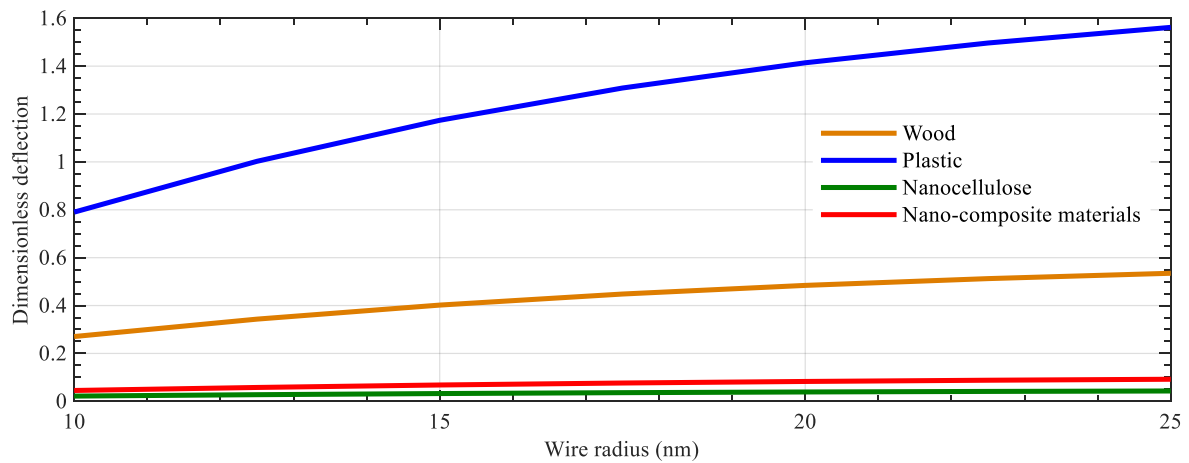


Fig. 2 Impact of the radius of nanowire on the bending deflection ( $(10\pi^2wE_{plastic}I/\eta L^3)$ ) due to the point load of regarding different material,  $l/L=1$ ,  $L=800$  (nm)

Table 1 Elastic modulus (E) and Poisson ratio ( $\nu$ ) of wood, plastic, and nanocellulose (Bodig and Jayne 1993, Harper 2000, Dufresne 2013, Srivastava and Kumar 2019)

	E (GPa)	$\nu$
Wood (Cedrella spp)	8.06	0.4
Plastic	2.76	0.4
Nanocellulose	100	0.4
Nanocomposite materials	46.1309	0.3

Table 2 Validity of dimensionless center deflection ( $100wEI/\eta L^3$ ) regarding the bending analysis (point load) in comparison to results of Reddy (2007)

	Deflection
Levinson beam theory (Reddy 2007)	1.9450
Reddy beam theory (Reddy 2007)	1.9449
Timoshenko theory (Reddy 2007)	1.9449
Classic beam theory (Reddy 2007)	1.9444

deflection associated with the wire made of different materials, including wood, plastic, nanocomposites, and nanocellulose, is investigated. Firstly, the variation of dimensionless mid-deflection of the wires is plotted versus the small-scale parameter in Fig. 1. It can be seen that the highest deflection is associated with the wire made of plastic, regardless of the small-scale factor value. Also, the wire made of nanocellulose has the lowest deflection. Also, it is apparent that the wire deflection is reduced by increasing the small-scale parameter, showing the stiffening effect of this parameter. It can be mentioned that the difference in deflection between the wires with different

constitutive materials is reduced by intensifying the small-scale factor.

Next, the wire's mid-deflection is plotted versus the wire radius in Fig. 2. Similar to the previous figure, the lowest deflection is related to the wires made of nanocellulose and nanocomposites. Also, the wire made of plastic has much higher deflection in comparison with the ones made of other materials. It is notable that the wire displacement is heightened by increasing the wire's radius. Also, it is interesting that the deflection of wires made of nanocellulose and nanocomposites are hardly at the mercy of wire radius.

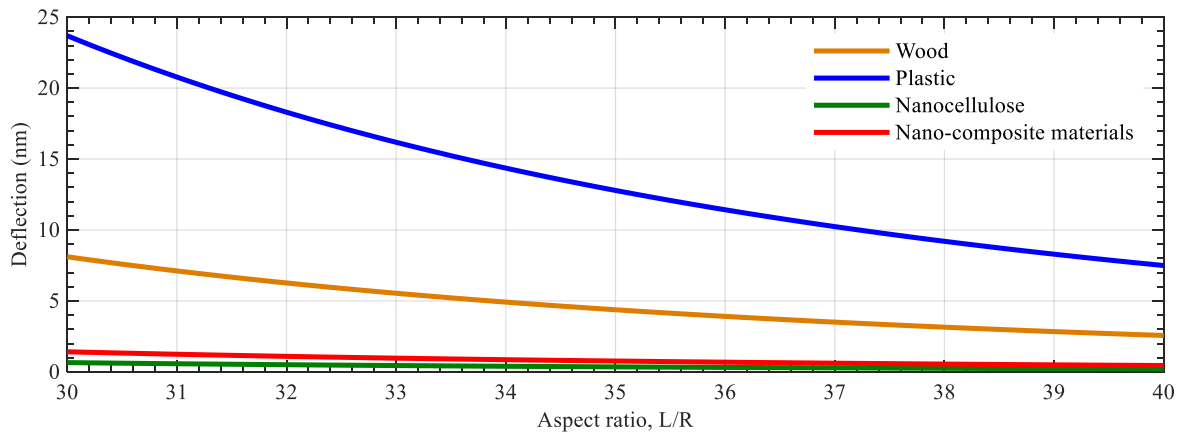


Fig. 3 Influence of aspect ratio ( $L/R$ ) on the central bending deflection of nanowire produced by different materials concerning the point load,  $R=30(\text{nm})$

Lastly, in order to investigate the effect of length to radius ratio on the static displacement of the wire, Fig. 3 is presented. This figure plots the wire deflection against the length to radius ratio. This figure indicates that the bigger the length to radius ratio is, the lower the deflection of the wire can be. However, this effect can be seen better in the wires made of plastics, and the difference between the deflection of the wire made of plastic and other materials is gotten lower as the higher values of the length to radius ratio is utilized.

#### 4. Conclusions

Plastics are the primary fundamental material for producing children's physical exercise equipment, however, they are hazardous to the environment, so the alternative materials that are harmless to the environment should be replaced. Wood is a good alternative, but they are limited, and its reproduction is timely and high-cost. In this regard, the current paper investigates the impact of using various types of materials such as plastic, wood, nanocellulose, and nanocomposites on the static bending of wires. The formulations of small-scale wire are obtained by means of the energy method as well as modified couple stress theory. The results are extracted via the Navier solution procedure. The results are validated by comparing them to those from other published data. The influence of factors such as small-scale parameters and geometrical factors on the mid-displacement of wires are explored, and here are some of the highlighted conclusions:

- The wire displacement is heightened by increasing the wire's radius.
- The bigger the length to radius ratio is, the lower the deflection of the wire can be.
- The highest deflection is associated with the wire made of plastic.
- The wire deflection is reduced by increasing the small-scale parameter, showing the stiffening effect of this parameter.
- The wire made of nanocellulose has the lowest deflection.

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